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RESEARCH ARTICLE

Strategic hybrid approach for selecting suppliers of high-density polyethylene

Miguel A. Ortiz Barrios[1] | Berk Kucukaltan[2] | Daniel Carvajal Tinoco[1] | Dionicio Neira Rodado[1] | Genett Jiménez[3]

[1] Department of Industrial Engineering, Universidad de la Costa CUC, Barranquilla, Colombia

[2] School of Applied Sciences, Trakya University, Edirne, Turkey

[3] Department of Industrial Engineering, Corporación Universitaria Reformada CUR, Barranquilla, Colombia

Correspondence
Miguel A. Ortiz Barrios, Department of Industrial Engineering, Barranquilla, Universidad de la Costa CUC, Calle 58 #55–66, Barranquilla 080003, Colombia.
Email: mortiz1@cuc.edu.co

Abstract

Supplier selection is an important process for companies in the plastic sector due to its influence on firm performance and competitiveness. For a proper selection, a number of criteria from different aspects need to be considered by decision makers. Yet, as in different fields, because there are numerous criteria and alternatives to be considered in the plastic industry, choosing an appropriate multicriteria decision-making approach has become a critical step for selecting suppliers. Therefore, the aim of this research is to define the most suitable supplier of high-density polyethylene through the integration of powerful multicriteria decision-making methods. For this purpose, the fuzzy analytic hierarchy process (FAHP) is initially applied to define initial weights of factors and subfactors under uncertainty, followed by the use of decision-making trial and evaluation laboratory (DEMATEL) to evaluate interrelations between the elements of the hierarchy. Then, after combining FAHP and DEMATEL to calculate the final contributions of both factors and subfactors on the basis of interdependence, the technique for order of preference by similarity to ideal solution is used to assess the supplier alternatives. In addition, this paper also explores the differences between the judgments of decision makers for both AHP and DEMATEL methods. To do these, a case study is presented to demonstrate the validity of the proposed approach.

KEYWORDS

competitiveness, DEMATEL, fuzzy AHP, plastic industry, supplier selection, TOPSIS

1 | INTRODUCTION

The impulse given in recent years to international trade has forced companies to face more competition. The rise in the number of competitors has encouraged companies to look for different strategies for increasing their competitiveness. However, augmentation of competitiveness requires considering various strategies, such as determination of and dealing with the costliest or inadequate process in a company. In this regard, companies need to focus on their core activities while choosing an outsourcing option from a supplier for their costliest processes. In parallel, on this matter, Peter Drucker stated, "Do what you do best and outsource the rest" (Tajdini & Nazari, 2012, p. 113). To this end, outsourcing is deemed by professionals as a commonly preferred option for increasing the competitiveness.

First, outsourcing is referred to as "outsource resource using" (Rezaeisaray, Ebrahimnejad, & Khalili-Damghani, 2016, p. 537), although there is no unique definition been agreed by researchers (Tajdini & Nazari, 2012). Nowadays, due to outsourcing attempts, companies have become more dependent on suppliers and this results in emphasizing more on the evaluation of suppliers' performance (Kannan, Govindan, & Rajendran, 2015; Viloria, 2016). Yet the importance of suppliers does not limit there; it also involves reviewing other factors, such as service, on time delivery, meeting stakeholders' expectations. Supply managers should consider all these factors in order to do a proper selection and evaluation of suppliers. The value of this process lies in the fact that it has a direct impact on firms' performance (Wetzstein, Hartmann, Benton, & Hohenstein, 2016) and their competitiveness. That is to say, suppliers are important sources for providing competitive advantages to companies (Koufteros, Vickery, & Dröge, 2012; Pulles et al., 2016) whereas they also contribute in delivering values to their customers (Prajogo, Oke, & Olhager, 2016). Therefore, selecting a suitable supplier is a pivotal parameter for companies, especially in terms of their competitiveness and performance growth.

In addition, the search for competitiveness requires focusing on different aspects of the organization. One of these aspects is the determination of an adequate way to measure and select suppliers. Suppliers are crucial for an organization because raw material represents in some organizations (e.g., alcohol industry), about 50% of the total cost (Vázquez & Dacosta, 2007). Being aware of the importance of this process, the next step is to choose the most suitable technique for supplier selection. In this regard, the first approaches in literature tackled the problem via focusing on selection criteria or mathematical optimization models using a set of criteria to select the best suppliers (Wetzstein et al., 2016). However, these models failed when including criteria that were not rigid but vague or ambiguous (Shaverdi, Heshmati, & Ramezani, 2014). Thus, it is necessary to combine different approaches to adequately address the supplier selection process (Simić, Kovačević, Svirčević, & Simić, 2016).

Various frameworks were developed for the purpose of selecting suppliers. These involved integrating both qualitative and quantitative measures (hybrid approaches) considering companies' goals. In this sense, multicriteria decision-making (MCDM) methods seem to be the suitable tool for weighting these qualitative and quantitative factors (Dargi, Anjomshoae, Galankashi, Memari, & Tap, 2014). Nevertheless, it is also important to consider vagueness and ambiguity of judgments (Shaverdi et al., 2014). Therefore, the incorporation of these aspects to MCDM made research merges the fuzzy linguistic approach to MCDM. The strength of fuzzy linguistic is due to its capability to represent the optimism/pessimism rating attitude of decision makers by triangular fuzzy numbers (Shaverdi et al., 2014).

As mentioned above, different MCDM approaches have become powerful tools to assist managers in decision making. These MCDM methods can be used by companies from different economic sectors; however, their impact is directly related to the company size. In this regard, hydrocarbon companies represent approximately 6.5% of world's GDP (World Economic Forum, 2016). Therefore, any important decision related with its value chain will affect the global economy.

Particularly, the impact of plastic companies on the world economy has been growing over the last 50 years. In this respect, the global plastic production rose from around 15 million metric tons (MMT) in 1964 to around 311 MMT in 2014 (World Economic Forum, 2016). Additionally, world's plastic production is projected to be approximately 1,124 MMT in 2050 (World Economic Forum, 2016). These estimations not only evidence how relevant the plastic industry is for world trade and economy but also imply the need to find ways to improve the companies' performance and their value chain.

The world's plastic production is largely represented by the container sector with approximately 40% of the total production (Paloma & Ortiz, 2012). Other relevant sectors (e.g., construction and consumption) represent 28% of global production (Paloma & Ortiz, 2012). In all these sectors, high-density polyethylene (HDPE) is one of the most critical raw materials and represents around 14% of world's plastic production (Paloma & Ortiz, 2012). On the other hand, each HDPE-based product (e.g., bottles, boxes, home elements, and pipes) must satisfy technical regulations and customer requirements. In this respect, the HDPE suppliers must be carefully selected to ensure meaningful insights focusing on the aforementioned aspects. Therefore, this paper aims to develop a combined fuzzy analytic hierarchy process (FAHP), decision-making trial and evaluation laboratory (DEMATEL), and technique for order of preference by similarity to ideal solution (TOPSIS) technique for supplier selection. The study was performed considering HDPE as the most critical raw for a company from the Colombian plastic industry.

The remainder of this paper is organized as follows: In Section 2, a literature review on techniques for MCDM supplier assessment and selection is presented whereas methods are explained in Section 3. In Section 4, a case study in the plastic industry is described. Then, in Section 5, results and analysis are shown. Finally, Section 6 presents conclusions.

2 | PRIMARY STUDIES FROM THE LITERATURE

Decision making is an activity that is repeatedly used in our daily lives (Mo & Deng, 2016) and is based on people's own (or group) values, understandings, and beliefs (Saaty, 2005). Because decision making is a fundamental activity including judgments and feelings, it belongs to some extent to meta-rational thinking (Saaty, 2004). From this point of view, due to the fact that making a decision is complex in nature (Kittur, Vijaykumar, Bellubbi, Vishal, & Shankara, 2015), especially for a single decision maker, group decision-making process is preferred to deal with this arduous task.

2.1 | Single MCDM approaches

In the group decision-making process, judgments of individual decision makers (or experts) are aggregated and a group choice is constructed. By doing this, the possible bias risk of a single decision maker (Kucukaltan, Irani, & Aktas, 2016; Van Horenbeek & Pintelon, 2014) can be avoided, and this advantage leads researchers to adopt the group decision-making process. While doing this, it is worthy of note that aggregating individual judgments in a mathematical way (e.g., as AHP does) is critical for obtaining a representative group judgment (Saaty, 2013). Therefore, implementing the techniques having a mathematical foundation is considered pivotal in this study.

In the literature, various MCDM techniques (e.g., data envelopment analysis (DEA), analytic network process (ANP), AHP, DEMATEL, TOPSIS, simple additive weighting, and PROMETHEE) are employed by researchers. Among these, researchers implement either a single MCDM technique (e.g., Daim, Udbye, & Balasubramanian, 2013; Dweiri, Kumar, Khan, & Jain, 2016; Vijayvargiya & Dey, 2010) or a hybrid approach (e.g., Chan, 2003; Hosseini & Al Khaled, 2016; Ustun & Demirtas, 2008) with the blend of two or more different methods. However, different methods hold different limitations in their structures. For instance, DEA, which presumes that all inputs and outputs are certainly known (Velasquez & Hester, 2013), measures the relative performance rather than the absolute (Rastar, Oobari, Digesarai, & Sadeghian, 2013) and cannot precisely present the real situation when the number of decision-making units is relatively small (Wu, Jia, & Yu, 2014). On the other hand, outcomes of simple additive weighting do not always reflect the real cases whereas PROMETHEE and TOPSIS do not present an explicit method in terms of allocating weights (Velasquez & Hester, 2013). Regarding AHP and TOPSIS, many authors concerned over some aspects of these methodologies. Particularly, ranking irregularities have been observed when using AHP. This situation is known as *rank reversal*, and it is related to the fact in which the preference order changes when removing or adding an alternative or criteria (Lima Junior, Osiro, & Carpinetti, 2014).

2.2 | Hybrid MCDM approaches

Due to the fact that selecting a suitable method is a considerable challenge and single MCDM methods can yield different results, it is recommended to implement a hybrid approach consisting of more than a single method (Zavadskas, Govindan, Antucheviciene, & Turskis, 2016). Furthermore, Zavadskas et al. (2016) noted that combining both subjective and objective measures importance into the value of utility function is an advantage for a hybrid approach over a single method. As a result, by considering the advantages of a hybrid approach and with the aim of offering more robust results by diminishing the limitations of different methods, a hybrid approach is decided to be used in this study.

2.3 | Applications to supplier selection and evaluation

In the supplier selection literature, it became apparent that different methods were integrated for different purposes. Some applications about the supplier selection problem can be exemplified as follows. Wang and Wu (2016) combined fuzzy DEMATEL, FAHP, and fuzzy Delphi for the assessment of programmable logic controller suppliers. They used DEMATEL to establish causality relationships and performed FAHP to generate weights for all criteria and subcriteria whereas fuzzy Delphi was carried out to assess performance scores of suppliers. Raut, Bhasin, and Kamble (2011) integrated AHP and fuzzy DEMATEL for the process of managing global supply chains. In another research, Alimardani, Rabbani, and Rafiei (2014) included DEMATEL, ANP, and TOPSIS techniques for evaluating the alternatives of agile suppliers.

In addition, Orji and Wei (2014) studied sustainable supplier selection, through the use of fuzzy logic, DEMATEL, and TOPSIS, based on a case study illustrated in a gear manufacturing company in China. In Rezaeisaray et al.'s (2016) study, a hybrid approach consisting of three methods, namely, DEMATEL, fuzzy ANP, and DEA, was proposed. In their two-stage process, the relation structure between the criteria was established by the DEMATEL and the weights and priorities of the criteria were determined by the fuzzy ANP in the first stage. In the second stage, the suppliers considered by a case company, a pipe and fitting manufacturer in Iran, were ranked through the DEA method. In another hybrid approach study, Sun, Huang, and Miao (2015) focused on supplier selection problem for the large equipment enterprise based on incomplete information. They combined DEMATEL, ANP, and TOPSIS methods with the D-S theory, which deals with decision fusion evaluation information from different decision makers, especially in the case of uncompleted information. In their study, DEMATEL was used to construct the relationship between the evaluation index sets of each supplier whereas ANP was applied to calculate weights for evaluation index sets and TOPSIS was performed for ranking in order to choose the most suitable supplier.

On the other hand, in supplier selection-related studies, plastic manufacturing processes were poorly considered by researchers. Only very few studies were found in the literature that describes the utilization of MCDM and particularly of FAHP, DEMATEL, and/or TOPSIS in plastic companies. Nevertheless, Ar, Göksen, and Tuncer (2015) described a process of selection and assessment of HDPE suppliers in a cable company in Turkey. The proposed approach used DEMATEL, ANP, and VIKOR methods in order to make the decision. They concluded that for this company, the price is the most important criterion. On the other hand, Stević, Tanackov, Vasiljević, Novarlić, and Stojić (2016) presented a supplier and evaluation process based on FAHP and TOPSIS for pipe suppliers. The process of selecting a polyethylene exposed in Florez Piña (2013) considered different factors focusing primary on the quality of the product, and quality assurance system of the supplier, but did not specify the weights assigned to each criterion neither the penalty for not meeting the target value. In this regard, Kannan et al. (2015) stated that supplier selection is a key function for an organization that can increase competitiveness. Additionally, they highlighted that the difficulty of evaluating various aspects of reality, especially using only a quantitative manner, makes the assessment process an MCDM problem with the inclusion of both quantitative and qualitative criteria. From this point of view, after using the Affinity Diagram method for developing criteria selection, they proposed the fuzzy axiomatic design method to select the best green supplier for a Singapore-based plastic manufacturing company. Yet the core concept of their study remained limited to the green aspect. Likewise, Ustun and Demirtas (2008) emphasized the multicriteria-based nature of supplier selection problem that contains both tangible and intangible criteria. In their paper, they constructed the problem into two stages. In the first stage, which is the evaluation phase, the ANP method was used to evaluate four different plastic moulding firms based on 14 criteria placed in four clusters, whereas, in the second stage, the shipment phase, multiperiod multiobjective mixed integer linear programming model was employed to obtain nondominated solutions. With a slight difference, but in the same context, Demirtas and Üstün (2008) performed both ANP and AHP in the first stage as well as making them serve as coefficients into the multiobjective mixed integer linear programming model that was used in the second stage.

2.4 | Reducing inconsistencies in group decision making

There exist multiple and mostly conflicting criteria for making decisions (Öztayşi & Uçal, 2009). In such cases, MCDM, which handles a problem in a structured and clear manner (Wu, Lin, & Lee, 2010), provides better solutions to overcome this difficulty that cannot be solved in a straightforward way. In this respect, human judgments and understanding play decisive roles for the difficulties at the strategic management level (Chai, Liu, & Ngai, 2013). That is to say, when there is a presence of multiple criteria and uncertain information, experience and knowledge regarding a problem play a crucial role and this explains why an eminent group of experts should be involved in a decision-making process (Poveda-Bautista, Baptista, & García-Melón, 2012). Accordingly, as subjective expert judgments are mainly implemented in the nature of MCDM approach, MCDM appears to be a rational approach for the success of this study (Ertuğrul & Karakaşoğlu, 2009).

In this regard, the cornerstone of the AHP method is the pairwise comparison (Meesariganda & Ishizaka, 2017), which enables decision makers to compare two elements at a time based on the fundamental 1–9 scale. In the literature, most AHP-related studies employ this fundamental scale (Joshi, Banwet, & Shankar, 2011; Shaik & Abdul-Kader, 2013); however, there are also some studies (e.g., Barrios et al., 2016; Meesariganda & Ishizaka, 2017; Pecchia et al., 2013; Wang, Qin, Li, & Chen, 2009) using a reduced scale. According to Huizingh and Vrolijk (1997), people allocate different numbers to the same verbal phrases and AHP overestimates the selection differences of decision makers. Therefore, they criticized Saaty's fundamental scale. Correspondingly, because the fundamental 1–9 scale was not deemed as the best scale for some researchers, using individual scales was recommended by Meesariganda and Ishizaka (2017) against the question regarding which scale to choose. In this respect, Pecchia et al. (2013) noted that applying a reduced scale is useful for reducing inconsistencies, due to the increase in significance to responders, and is easier for decision makers, who are not qualified in complex mathematics or with the AHP technique, to understand the process. Likewise, Barrios et al. (2016) used a reduced scale in order to avoid loss of interest and distractions that may influence the decision consistency. From this point of view, we similarly employed a reduced scale, from 1 to 5, in this study in order both to help decision makers in terms of increasing the clarity of pairwise comparisons while assigning scores and to reduce the inconsistencies throughout the process.

Additionally, in order to overcome the lack of certainty occurring from human subjective judgments, uncompleted preference relationships, and to provide a more realistic model (Zavadskas et al., 2016), fuzzy logic is applied to the use of the AHP method in the present study. The rationale of using a fuzzy approach is similar with Kannan et al.'s (2015) supplier selection-related study where they explained that the responses of their decision makers were linguistic, incomplete, and inexact. Thus, by following the fuzzy approach, it was intended to make decision makers more confident while giving interval judgments, rather than fixed values, as similarly emphasized by Ertuğrul and Karakaşoğlu (2009).

Considering the literature, the newest trend regarding the use of MCDM methods is to employ two or more techniques (Barrios et al., 2016). However, because the purpose of this paper is not to examine the MCDM methods in detail, we only highlighted the most common methods. In light of these, the conducted literature review practice showed that studies directly concentrating on supplier selection with the use of FAHP, TOPSIS, and DEMATEL are largely limited. Therefore, we implemented a hybrid approach in this study in order to provide a useful decision-making tool that can be used as a preferential system in realistic scenarios. In addition, a reduced AHP scale from 1 to 5 was used to reduce inconsistencies throughout the process.

3 | METHODS

3.1 | Description of the proposed methodology

The proposed methodology aims to select the best supplier of HDPE in companies from the plastic sector. This approach is composed of six phases. First, a *decision-making group* is established to design the hierarchy and make pairwise comparisons between factors and subfactors for both FAHP and DEMATEL methods. Then, a hierarchic structure is arranged based on the personal experience of decision makers and the pertinent scientific literature. After this, FAHP is performed to elicit the criteria and subcriteria weights. FAHP is used to deal with the experts' ambiguities during the *decision-making process*. Afterward, DEMATEL is applied to evaluate interrelations between criteria and subcriteria. The collected FAHP and DEMATEL judgments are also compared through correlation analysis, tests for differences between means and factor analysis (α level = 0.05) to establish possible similarities between the perceptions of the experts. The goal of this phase is to explore the differences between the experts' judgments when selecting suppliers of HDPE. In this sense, we can find out whether needs' importance, influence between criteria and subcriteria, and ranking of alternatives are homogeneous according to the expert profile. This is a relevant output when comparing the results of this application with others emanating from other similar studies. Additionally, this analysis has been widely performed in AHP-based studies (Pecchia, Bath, Pendleton, & Bracale, 2010; Pecchia et al., 2013; Scholl, Manthey, Helm, & Steiner, 2005) with the purpose of eliciting needs. Finally, TOPSIS ranks the suppliers according to their closeness coefficient. Figure 1 summarizes the proposed methodology. **F1**

3.2 | Fuzzy analytic hierarchy process

Because AHP does not consider vagueness of human judgments, the fuzzy logic theory was introduced due to its capability of representing imprecise data. In FAHP, the paired comparisons are represented by triangular numbers (Ayhan, 2013; Kilincci & Onal, 2011) as described below (refer to Table 1). Considering the findings from literature **T1** review, a reduced AHP scale has been adopted by the decision makers when making comparisons.

Below is the description of FAHP algorithm:

- Perform pairwise comparisons between criteria and subcriteria by using the linguistic terms and the corresponding fuzzy triangular numbers established in Table 1. With these data, a fuzzy judgment matrix $\tilde{A}^k(a_{ij})$ is obtained as described below in Equation 1:

$$\tilde{A}^K = \begin{bmatrix} \tilde{d}_{11}^k & \tilde{d}_{12}^k & \dots & \tilde{d}_{1n}^k \\ \tilde{d}_{21}^k & \tilde{d}_{22}^k & \dots & \tilde{d}_{2n}^k \\ \dots & \dots & \dots & \dots \\ \tilde{d}_{n1}^k & \tilde{d}_{n2}^k & \dots & \tilde{d}_{nn}^k \end{bmatrix}, \quad (1)$$

$\tilde{d}_{ij}^k$ indicates the kth expert's preference of ith criterion over jth criterion via fuzzy triangular numbers.

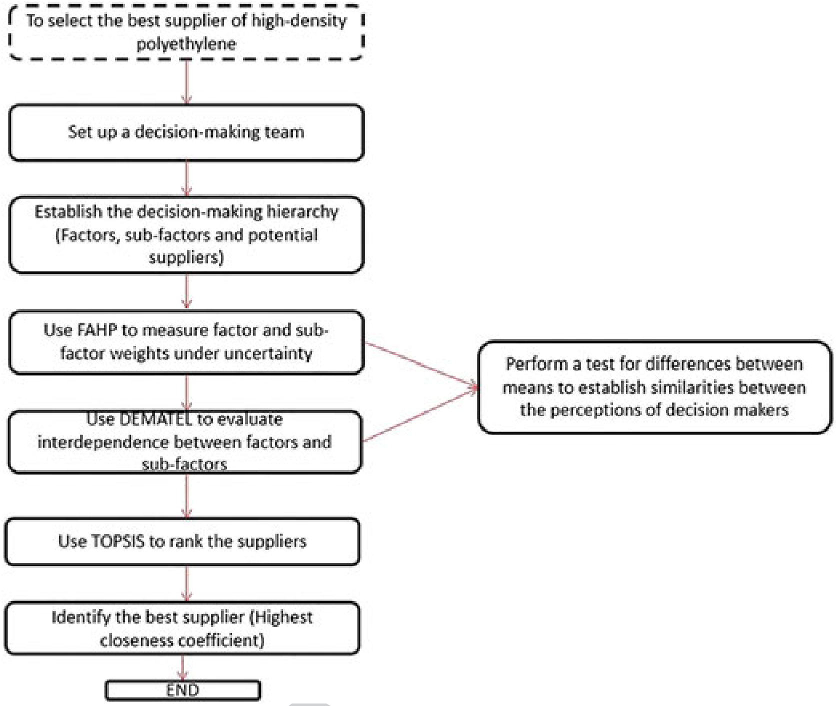

FIGURE 1 Proposed methodology for selecting suppliers of high-density polyethylene

- In the case of a focus group, the judgments are averaged according to Equation 2, where K represents the number of experts involved in the decision-making process. Then, the fuzzy judgment matrix is updated as shown in Equation 3.

$$\widetilde{d}_{ij} = \frac{\sum_{k=1}^{K} \widetilde{d}_{ij}^{k}}{K}, \tag{2}$$

$$\widetilde{A} = \begin{bmatrix} \widetilde{d_{11}} & \cdots & \widetilde{d_{1n}} \\ \vdots & \ddots & \vdots \\ \widetilde{d}_{n1} & \cdots & \widetilde{d}_{nn} \end{bmatrix}. \tag{3}$$

- Calculate the geometric mean of fuzzy judgment values of each factor by using Equation 4. Here, $\widetilde{r}_i$ denotes triangular numbers.

$$\widetilde{r}_i = \left(\prod_{j=1}^{n} \widetilde{d}_{ij}\right)^{1/n}, i = 1, 2, \ldots, n. \tag{4}$$

TABLE 1 Linguistic terms and their fuzzy triangular numbers

Reduced AHP scale	Definition	Fuzzy triangular number
1	Equally important	[1,1,1]
3	More important	[2,3,4]
5	Much more important	[4,5,6]
1/3	Less important	[1/4,1/3,1/2]
1/5	Much less important	[1/6,1/5,1/4]

- Determine the fuzzy weights of each factor $(\widetilde{w}_i)$ by applying Equation 5.

$$\widetilde{w}_i = \widetilde{r}_i \otimes (\widetilde{r}_1 \oplus \widetilde{r}_2 \oplus \ldots \oplus \widetilde{r}_n)^{-1} = (lw_i, mw_i, uw_i). \tag{5}$$

- Defuzzify $(\widetilde{w}_i)$ by performing Centre of Area method (~~Chou and Chang, 2008)~~ via using Equation 6. M_i is a nonfuzzy number. Then, normalize M_i via applying Equation 7. Q7

$$M_i = \frac{lw_i + mw_i + uw_i}{3}, \tag{6}$$

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i}. \tag{7}$$

3.3 | Decision-making trial and evaluation laboratory

DEMATEL is an MCDM technique that effectively pinpoints causal relationships in complex decision-making hierarchies (Liou, Yen, & Tzeng, 2008; Wu, 2008). Q8 Because DEMATEL is based upon the graph theory, the final product is a visual representation that categorizes the factors into two groups: receivers and dispatchers (Hung, 2011). *Dispatchers* are the criteria/subcriteria that highly influence other criteria/subcriteria whereas the affected factors/subfactors are called *Receivers*. To do this, DEMATEL converts the relations between criteria's causes and effects into a structural mapping model (Su et al., 2016) Additionally, this method indicates the influence degree of each element, so that significant interdependences can be identified (Wei, Huang, Tzeng, & Wu, 2010).

The steps of the DEMATEL method are explained as follows:

- *Find the direct-relation matrix*: To analyse interdependence, a committee of experts is asked to perform paired comparisons between criteria and subcriteria based on their personal experience. Each *decision maker* specifies how the criterion/subcriterion i influences on criterion/subcriterion j via applying a comparison scale ranging from 0 to 4: *no influence* (0), *low influence* (1), *medium influence* (2), *high influence* (3), and *very high influence* (4). With these judgments, an average matrix called direct-relation matrix $\boldsymbol{Z}$ is thus obtained (refer to Equation 8). Each z_{ij} value denotes the average degree to which the criterion/subcriterion i affects the criterion/subcriterion j. The value on any element on the diagonal is 0.

$$Z = \begin{bmatrix} 0 & z_{12} & \dots & z_{1n} \\ z_{21} & 0 & \dots & z_{2n} \\ \dots & \dots & \ddots & \dots \\ z_{n1} & z_{n2} & \dots & 0 \end{bmatrix}. \tag{8}$$

- *Calculate the normalized direct-relation matrix*: Using Equations 9 and 10, normalized matrix can be derived from direct-relation matrix $\boldsymbol{Z}$:

$$X = s \cdot Z, \tag{9}$$

$$s = \min\left(\frac{1}{\max 1 \le i < n \sum_{j=1}^{n} |z_{ij}|}, \frac{1}{\max 1 \le j < n \sum_{i=1}^{n} |z_{ij}|}\right) i, j \in \{1, , , 2, , , 3, \dots, n\}. \tag{10}$$

- *Compute the total-relation matrix*: After calculating the normalized direct-relation matrix X, the total-relation matrix T is obtained by applying Equation 11 where I represents the identity matrix:

$$T = X + X^2 + X^3 + \dots = \sum_{i=1}^{\infty} X^i = X(I - X)^{-1}. \tag{11}$$

- *Identify the dispatchers and receivers*: Using $D - R$ values, where R_i is the sum of the *jth* column of matrix T (refer to Equations 12–13) and D_i is the sum of the *ith* row (refer to Equations 12 and 14), cause and effect groups can be determined. In this regard, factors/subfactors with negative $D - R$ value are categorized as *receivers*, whereas positive values indicate *dispatcher* elements. On the other hand, $D + R$ values represent the strength of influence between the system elements; however, the significant interdependences are identified via using Len's method as described in the next step.

$$T = [t_{ij}]_{nxn}, i, j \in \{1, , , 2, , , 3, \dots, n\}, \tag{12}$$

$$R = \sum_{j=1}^{n} t_{ij}, \tag{13}$$

$$D = \sum_{i=1}^{n} t_{ij}. \tag{14}$$

- *Define the threshold value and identify significant influences*: DEMATEL threshold value is proposed to be calculated through Lenth's method (Hsieh, Lee, & Lin, 2016; Lenth, 1989) because it eliminates non-significant interdependences in scenarios with complex decision-making hierarchies. Therefore, when this technique is integrated with DEMATEL, the suitable threshold value can be obtained and problems resulting from the inadequate calculation of this index can be effectively solved. Lenth's method can be summarized as follows:
  - ○ Calculate the initial estimate of threshold value S_o by using Equation 15.

$$S_o = 1.5^{*} \underset{1 \le k \le m}{\text{median}} \left|\widehat{\beta}_k\right|. \tag{15}$$

  - ○ Compute the pseudostandard error (PSE) by using Equation 16. PSE indicates the median resulting from the absolute regression coefficients that are smaller than 2.5 S_o:

$$PSE = 1.5 * \underset{\left|\widehat{\beta}_k\right| < 2.5 S_o}{\text{median}} \left|\widehat{\beta}_k\right|. \tag{16}$$

  - ○ Determine the margin error of regression coefficients via applying Equation 17. An influence lower than margin error is considered as non-significant.

$$ME = t_{1-\frac{\propto}{2}, \frac{m}{3}}{}^{*} PSE. \tag{17}$$

3.4 | Technique for order of preference by similarity to ideal solution

TOPSIS is a *decision-making* technique that involves selecting the alternative with the shortest distance from the positive ideal solution (PIS) and the farthest distance from negative ideal solution (NIS; Dymova, Sevastjanov, & Tikhonenko, 2013). PIS is composed of all the best attribute values achievable, whereas NIS considers the worst attribute measures (Khorshidi, Hassani, Rauof, & Emamy, 2013). Nevertheless, the selected alternative that has the minimum Euclidean distance from PIS may also have a short distance from NIS. Furthermore, a simple assumption is that each criterion is characterized by either monotonically increasing or decreasing utility (Chamodrakas, Leftheriotis, & Martakos, 2011). Therefore, TOPSIS tries to find alternatives that are simultaneously close to PIS and far from NIS via using the relative closeness coefficient (Shanian & Savadogo, 2006). The procedure of TOPSIS is described as follows:

- Set a decision matrix X with "m" suppliers of HDPE and "n" subfactors (refer to Equation 18). X_{ij} is the value of the subfactor S_j $(j = 1, 2, 3, \dots, n)$ in each HDPE supplier $P_i (i = 1, 2, \dots, m)$.

$$X = \begin{matrix} \\ P_1 \\ P_2 \\ P_3 \\ : \\ P_m \\ \\ \end{matrix} \begin{bmatrix} S_1 & S_2 & \dots & S_n \\ x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ x_{31} & x_{32} & \dots & x_{3n} \\ : & : & \dots & : \\ x_{y1} & x_{y2} & \dots & x_{yn} \end{bmatrix}. \tag{18}$$

- Obtain the normalized decision matrix R by using Equation 19. Let n_{ij} be the norm used by TOPSIS (refer to Equation 20). In addition, r_{ij} is defined as the element of this matrix.

$$R = Xn_{ij}, \tag{19}$$

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{y} x_{ij}^2}}. \tag{20}$$

- Calculate the weighted normalized decision matrix V (refer to Equation 21). The set of subfactor weights (w_j) derive from the combined FAHP–DEMATEL technique.

$$V = \left[w_j r_{ij}\right] = \left[v_{ij}\right]. \tag{21}$$

- Define the ideal (C^+) and anti-ideal (C^-) scenarios according to Equations 22 and 23 correspondingly:

$$\begin{aligned} C^+ &= \left\{\left(\max_i c_{ij} \mid j \in J\right), \left(\min_i c_{ij} \mid j \in J^{\text{Ë}}\right) for\ i = 1, 2, \ldots, m\right\} \\ &= \left\{c_1^+, c_2^+, \ldots, c_j^+, \ldots, c_n^+\right\}, \end{aligned} \tag{22}$$

$$\begin{aligned} C^- &= \left\{\left(\min_i c_{ij} \mid j \in J\right), \left(\max_i c_{ij} \mid j \in J^{\text{Ë}}\right) for\ i = 1, 2, \ldots, m\right\} \\ &= \left\{c_1^-, c, \ldots, c_j^-, \ldots, c_n^-\right\}, \end{aligned} \tag{23}$$

where

$$J = \{j = 1, 2, \ldots, n \mid j\ associated\ with\ the\ benefit\ sub\text{-}criterion\},$$

$$J^{\text{Ë}} = \{j = 1, 2, \ldots, n \mid j\ associated\ with\ the\ cost\ sub\text{-}criterion\}.$$

- Calculate the separation measures of each HDPE supplier to the ideal and anti-ideal scenario by using Euclidean separation described in Equations 24–25.
  Separation from ideal scenario

$$d_i^+ = \sqrt{\sum_{j=1}^{n}\left(c_{ij} - c_j^+\right)^2} \qquad i = 1, 2, \ldots, m. \tag{24}$$

Separation from anti-ideal scenario

$$d_i^- = \sqrt{\sum_{j=1}^{n}\left(c_{ij} - c_j^-\right)^2} \qquad i = 1, 2, \ldots, m. \tag{25}$$

- Obtain the relative closeness coefficient (R_i) by applying Equation 26. If $R_i = 1$, the supplier performs according to d_i^+; thus, larger values of R_i represents satisfactory overall performances.

$$R_i = \frac{d_i^+}{\left(d_i^+ + d_i^-\right)}, \quad 0 < R_i < 1, \quad i = 1, 2, \ldots, m. \tag{26}$$

- Rank the HDPE suppliers according to the preference order of R_i.

4 | DESCRIPTION OF A CASE STUDY IN THE PLASTIC INDUSTRY

In this section, an empirical example is presented to validate the proposed methodology. The case study is illustrated in a medium-sized plastic manufacturer located in Colombia. The company is a wholesale supplier of flexible packaging, plastic bags, and pipes that are produced from HDPE. In addition, it supplies a wide range of products for use in many applications, from the textile industry to the food industry, with a customer base reaching from Colombia to Latin America. In this regard, the company focuses on continuously satisfying the customer requirements (e.g., quality, delivery date, price, innovation, and service level) to improve firm performance and subsequently to address the increasing number of competitors in the plastic industry. To support these strategies, the manufacturer has identified the need of adequately select its HDPE suppliers, and thus, it is necessary to design a decision-making model that ranks the potential suppliers according to a predefined set of criteria and subcriteria.

This study was previously discussed with the company's chief executive who gave informed consent to participate in this research. The decision-making process was led by two academics who are the co-authors of this paper. Furthermore, the focus group involved three managers who headed different departments of the company. A summary of the participants' profile is described below:

- *The Chief executive*, with more than 5 years of experience in the plastic sector
- *Three managers* (Head of Production Department, Head of Quality Department, and Head of Purchasing Department), who have a wide experience in plastic production.
- *One professor from an Industrial Engineering Department*, with extensive experience and knowledge in decision making and supplier selection process.
- *One earlier researcher from an Industrial Engineering Department*, with knowledge in decision-making techniques.

The *Chief executive* was included in the team of experts because he has performed as part of the administrative and financial staff in companies from the plastic sector; thus, he has valuable experience to make precise judgments about the importance of criteria and subcriteria when selecting HDPE suppliers. The *managers* were also invited to be part of the decision-making team due to their knowledge and career path regarding supply chain management, plastic production, and quality standards for HDPE. On the other hand, the *professor* designed the hierarchic model with the support of the experts and the *earlier researcher* collected the paired comparisons for both FAHP and DEMATEL methods. In addition, this *researcher* gathered data required to implement TOPSIS.

The experts identified **eight factors** and **21 subfactors** to select the best supplier of HDPE. In this particular case, **five HDPE suppliers** were evaluated (P1, P2, P3, P4, and P5). Both criteria and subcriteria were determined considering the experts' experience, industry measures, and the pertinent scientific literature (Chen, Lin, & Huang, 2006; Ho, Xu, & Dey, 2010; Pi & Low, 2006; Wood, 2016). The MCDM model was verified and discussed during several visits with the expert's group to check if it was comprehensible. The resulting decision model is shown in Figure 2.

The description of each factor is detailed as follows:

- QUALITY (C1) is defined as the degree to which the supplied HDPE meets the government regulations and customer requirements.
- PRODUCTIVITY (C2) is described as the ratio of output per kilogram of HDPE used in the production process. This is to measure how the technical characteristics of a specific HDPE type influence on the company's production performance.
- SERVICE LEVEL (C3) factor refers to the level of service expected by the manufacturer from the HDPE supplier in terms of lead time, flexibility, and customer service.
- COMMERCIAL POLICY (C4) factor represents the current commercial performance of the HDPE supplier and the terms to initiate a long-term manufacturer–supplier relationship.
- PRODUCT PRESENTATION (C5) considers the cleanliness and packing conditions offered by the supplier for the appropriate delivery of HDPE. Furthermore, it takes into account whether the supplier is capable of providing the standard documentation required during the delivery process.
- INNOVATION (C6) criterion measures the supplier's capability to generate profitable value-added HDPE and to improve differentiation while reducing costs.
- SUPPLIER LOCATION (C7) considers the physical distance between the HDPE supplier and the company.
- FINANCIAL PERFORMANCE (C8) represents the payment conditions imposed by the HDPE supplier and its financial stability.

Below is a description for each subfactor. First, the QUALITY factor (C1) is composed of three subcriteria: FDA CERTIFICATE (S1), PRODUCT WITH SAFETY DATA (S2), and APPROVED PRODUCT (S3). In this respect, FDA CERTIFICATE considers whether the supplier provides a document prepared by FDA (Food and Drug Administration) containing information about the HDPE's regulatory or marketing status. On the other hand, PRODUCT WITH SAFETY DATA evaluates if the supplier gives relevant material data safety sheet required to understand the hazards and safety precautions when manipulating HDPE. Another QUALITY subfactor is APPROVED PRODUCT, which assesses if the provider keeps HDPE approved according to the accreditation standards and requirements.

The PRODUCTIVITY criterion (C2) is composed of four subfactors: PRODUCTION CAPACITY (S4), MACHINE PERFORMANCE (S5), TECHNICAL CAPACITY (S6), and PRODUCT DESIGN (S7). PRODUCTION CAPACITY defines the volume of HDPE that can be generated by the supplier's production plant in a year by using current resources. Another PRODUCTIVITY factor is MACHINE PERFORMANCE that represents the efficiency level of the company's extrusion machine. Apart from this subcriterion, it is important to take into account the TECHNICAL CAPACITY of suppliers, which considers the technological capabilities to achieve new product advantages. This is complemented by the PRODUCT DESIGN subcriterion that evaluates whether the supplied HDPE performs its intended functionality

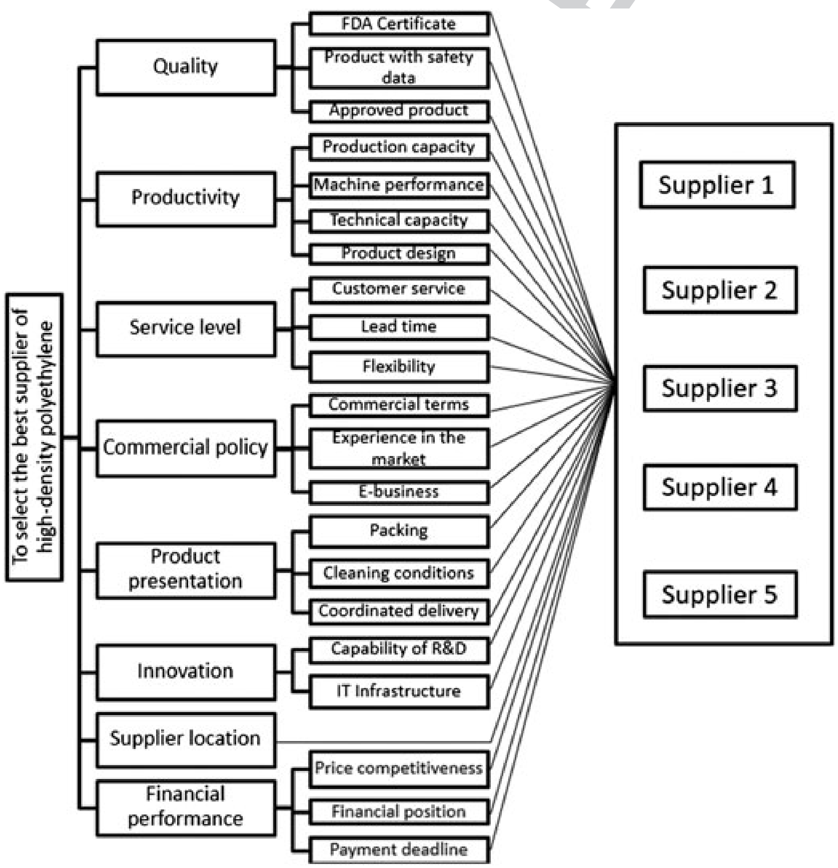

FIGURE 2 Hierarchy for selecting providers of high-density polyethylene

in an efficient, reliable, and safe manner. In addition, it assesses if this product is capable of being produced economically and to be attractive to targeted consumers.

The SERVICE LEVEL factor (C3) is defined by three subcriteria: CUSTOMER SERVICE (S8), LEAD TIME (S9), and FLEXIBILITY (S10). CUSTOMER SERVICE considers the service provided by the HDPE supplier before, during, and after purchase. On the other hand, LEAD TIME measures the average period ranging from the time an order is received by the supplier to the time the order is delivered to the company's manufacturing plant. Another SERVICE LEVEL subfactor is FLEXIBILITY that assesses the supplier's ability to react to environmental uncertainty with little penalty, effort, cost, or performance (Upton, 1994)

The COMMERCIAL POLICY criterion is divided into three categories: COMMERCIAL TERMS (S11), EXPERIENCE IN THE MARKET (S12), and E-BUSINESS (S13). First, COMMERCIAL TERMS subcriterion refers to a set of requirements imposed by HDPE suppliers to establish contractual agreements with a company from the plastic sector. The next category (EXPERIENCE IN THE MARKET) indicates whether the supplier has been in business for a long time. This is an evidence of stability in the market and results in formulating corporate competitive strategies. The third category (E-BUSINESS) evaluates whether the supplier can provide the company with the ability to place orders and get information without calling. In this regard, Sanders (2007) demonstrated that the supplier use of e-business technologies positively impacts organizational goals both directly and indirectly by promoting buyer–supplier coordination.

Considering the hierarchy from Figure 2, PRODUCT PRESENTATION factor is defined through three categories: PACKAGING (S14), CLEANING CONDITIONS (S15), and COORDINATED DELIVERY (S16). The first category (PACKAGING) establishes whether the supplier provides appropriate packaging that protects HDPE from damage by freight and parcel carriers during handling and transportation. The second subcriterion (CLEANING CONDITIONS) evaluates if the HDPE provider keeps the product free from impurities and contaminants. In this respect, Santana and Gondim (2009) determined that some substances influence on the oxidation degradation of HDPE; and thus, it is necessary to ensure favourable cleaning conditions during storage and transportation. Another category is COORDINATED DELIVERY that determines if the provider attempts to meet the promised delivery date. This is relevant when considering that failing to meet customer expectations is the quickest way to destroy reliability (Urban, Sultan, & Qualls, 2000).

To properly define INNOVATION criterion, two decision elements were considered: CAPABILITY OF R&D (S17) and IT INFRASTRUCTURE (S18). The S17 subfactor measures the supplier's ability to create improved versions of HDPE. This is important by considering that R&D capabilities have been determined as a prime competence to differentiate between successful and unsuccessful firm performance (Azar & Drogendijk, 2014; Nerkar & Paruchuri, 2005). On the other hand, IT INFRASTRUCTURE is defined as the supplier's collection of composite hardware, software, network resources, data centres, facilities, and technical equipment used to develop, operate, monitor, manage, and support information technology services during supplier–customer collaborations.

In order to adequately measure FINANCIAL PERFORMANCE of HDPE suppliers, three subcriteria were taken into account: PRICE COMPETITIVENESS (S19), FINANCIAL POSITION (S20), and PAYMENT DEADLINE (S21). First, PRICE COMPETITIVENESS subfactor evaluates the HDPE price established by a particular provider compared to published pricing information from other companies offering similar products. Another subcriterion is FINANCIAL POSITION that measures the overall financial status of the supplier by analysing the data available on its financial statement. By gathering key financial information on suppliers, the company can reduce the risks introduced to its operations when partnering with a third-party firm (Monczka, Handfield, Giunipero, & Patterson, 2015; Sadgrove, 2016). In addition to the aforementioned subfactors, PAYMENT DEADLINE was also contemplated to evaluate the financial status of suppliers. This subcategory considers the potential due date of invoices provided by the suppliers with basis on the contractual supplier–customer agreements specified in the "trading terms" subsection. In this regard, short payment periods may negatively affect the financial stability of the company; thus, this variable must be carefully studied when selecting suppliers of HDPE (Lamoureux & Evans, 2011; More & Basu, 2013)

5 | MODEL VALIDATION

This section describes how the case company applied our proposed approach to select the most suitable supplier of HDPE. As a result, the most important and influencing criteria and subcriteria were analytically identified. In addition, the ranking of HDPE providers was established according to the closeness coefficient values. More detailed results are provided below considering the methodology structure described in Section 3.1.

5.1 | Phase 1: Survey design for AHP and DEMATEL

A data collection instrument (refer to Figure 3) was created to gather F3
the paired comparisons performed by the expert team. Then, by using Equations 1–7, criteria and subcriteria weights were determined. For each pairwise judgment, it was asked: *With respect to goal/factor, ¿how important is each element on the left over the element on the right?* The participants answered by using the scale described in Table 1. This process was then repeated until completing all the judgments. Particularly, the design of this instrument contributed to minimizing discrepancies and lack of comprehension. Additionally, it excluded intransitive comparisons during the decision-making process.

Likewise, a similar survey was designed for DEMATEL (refer to
Figure 4) in order to analyse interdependence between factors and F4
subfactors. Then, by applying Equations 8–17, dispatchers and receivers were identified. For each comparison, it was asked: *With respect to goal/factor, ¿how much influence each element on the left has over the element on the right?* The experts responded by using the 5-point scale shown in Section 3.3. The decision process was also repeated to finally calculate $D + R$ and $D - R$ values.

With respect to "Service level", ¿how important is each element on the left over the element on the right?								
Customer Service	is	Much less	Less	Equally	More	Much more	Important than	Lead time
Customer Service	is	Much less	Less	Equally	More	Much more	Important than	Flexibility
Flexibility	is	Much less	Less	Equally	More	Much more	Important than	Lead time

FIGURE 3 Data collection instrument for analytic hierarchy process judgments

With respect to "Quality", ¿how much influence each element on the left has over the element on the right?								
FDA Certificate	has	No	Low	Medium	High	Very high	Influence over	Product with safety data
FDA Certificate	has	No	Low	Medium	High	Very high	Influence over	Approved product
Product with safety data	has	No	Low	Medium	High	Very high	Influence over	Approved product
Product with safety data	has	No	Low	Medium	High	Very high	Influence over	FDA Certificate
Approved product	has	No	Low	Medium	High	Very high	Influence over	FDA Certificate
Approved product	has	No	Low	Medium	High	Very high	Influence over	Product with safety data

FIGURE 4 Data collection instrument for DEMATEL comparisons. DEMATEL = decision-making trial and evaluation laboratory

5.2 | Phase 2: Global and local weights of criteria and subcriteria

Via integrating FAHP and DEMATEL techniques, the local and global contributions of subcriteria were determined to take into account linear dependence, interrelations, and uncertainty environments. To do this, the fuzzy judgment matrixes were initially computed based on the pairwise comparisons performed by the decision makers. An example of this matrix is shown in Table 2.

Then, by applying Equation 4, the geometric means of fuzzy comparisons were calculated. An illustration of these results is shown in Table 3. Additionally, by using Equations 5–7, the normalized weights of factors and subfactors were obtained (refer to Table 4). The fuzzy and nonfuzzy weights of factors have been described in Table 5 to evidence the subresults of the FAHP procedure.

The inconsistency values (consistency ratio) were also determined (refer to Table 6). Because these indexes are not higher than 10%, the estimates of weights can be accepted. In this respect, the 10% consistency limit appears to be a sufficient measure to ensure that the eigenvector follows the Dirichlet distribution with a set of parameters that can be derived from the corresponding matrix (Saaty, 2013; Saaty & Vargas, 2013). Therefore, the data gathering process can be considered satisfactory and, subsequently, the decision-making process with highly reliable results.

Then, in order to estimate the weights of criteria (NF_i) and subcriteria (NG_i) on the basis of interdependence (WF_c, WG_c), the weights obtained from FAHP application are multiplied with the normalized direct-relation matrix X as indicated in Equations 27–28:

$$WFc = \begin{matrix} \\ P_1 \\ P_2 \\ P_3 \\ \vdots \\ P_m \\ \\ \end{matrix} \begin{bmatrix} S_1 & S_2 & \dots & S_n \\ x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ x_{31} & x_{31} & \dots & x_{3n} \\ \vdots & \vdots & \dots & \vdots \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{bmatrix}^{*} \begin{bmatrix} NF_1 \\ NF_2 \\ NF_3 \\ \vdots \\ NF_k \end{bmatrix}, \quad (27)$$

TABLE 2 Fuzzy judgment matrix for "factors"

	C1	C2	C3	C4	C5	C6	C7	C8
C1	[1,1,1]	[2,2.5,3]	[1.5,2,2.5]	[2.6,3.3,4.1]	[2,2.5,3]	[3.5,4.5,5.5]	[2.8,3.5,4.3]	[1.8,2,2.3]
C2	[0.6,0.6,0.7]	[1,1,1]	[2,2.5,3]	[2.3,3,3.8]	[2,3,4]	[1.1,1.3,1.6]	[2.8,3.5,4.3]	[1.3,1.5,1.8]
C3	[0.6,0.7,0.8]	[0.6,0.6,0.7]	[1,1,1]	[1.3,1.8,2.4]	[2,2.5,3]	[0.6,0.7,0.8]	[1.3,1.5,1.8]	[0.7,1,1.4]
C4	[0.6,0.9,1.3]	[0.4,0.5,0.6]	[0.9,1.2,1.5]	[1,1,1]	[2.5,3.3,4.1]	[0.9,1.1,1.4]	[0.6,0.7,0.8]	[0.8,0.8,0.9]
C5	[0.6,0.6,0.7]	[0.3,0.3,0.5]	[0.6,0.6,0.7]	[1.1,1.4,1.8]	[1,1,1]	[0.7,1,1.4]	[1.8,2.3,2.8]	[0.6,0.7,0.8]
C6	[0.2,0.2,0.3]	[1.1,1.3,1.6]	[1.5,2,2.5]	[1.8,2.3,2.9]	[1.6,2.3,3.1]	[1,1,1]	[1.6,2.3,3.1]	[1.1,1.3,1.6]
C7	[0.4,0.4,0.5]	[0.4,0.4,0.5]	[0.8,0.8,0.9]	[1.5,2,2.5]	[1.4,1.6,1.9]	[0.7,1,1.4]	[1,1,1]	[1,1.3,1.6]
C8	[0.8,0.8,0.8]	[0.8,0.8,0.9]	[1.6,2.3,3.1]	[1.3,1.5,1.8]	[1.5,2,2.5]	[1.1,1.3,1.6]	[1.6,1.8,2.1]	[1,1,1]

TABLE 3 Geometric means of fuzzy comparisons for "factors" cluster

Criterion	C1	C2	C3	C4	C5	C6	C7	C8
Geometric mean of fuzzy comparisons	[2.21,2.79,3.36]	[1.53,1.93,2.33]	[0.91,1.1,1.31]	[0.82,1.01,1.22]	[0.7,0.84,1.03]	[1.05,1.4,1.79]	[0.78,0.94,1.12]	[1.18,1.42,1.65]

TABLE 4 Normalized fuzzy weights for “factors” cluster

Fuzzy weight				Nonfuzzy weight	Normalized weight
C1	0.16	0.24	0.37	0.26	0.243
C2	0.11	0.17	0.25	0.18	0.168
C3	0.07	0.10	0.14	0.10	0.096
C4	0.06	0.09	0.13	0.09	0.089
C5	0.05	0.07	0.11	0.08	0.074
C6	0.08	0.12	0.19	0.13	0.124
C7	0.06	0.08	0.12	0.09	0.083
C8	0.09	0.12	0.18	0.13	0.123
Total				1.06	

TABLE 5 Local and global contributions of criteria and subcriteria by using FAHP

Cluster	GW	LW
Quality (C1)	**0.243**	
FDA certificate	0.088	0.361
Product with safety data	0.092	0.379
Approved product	0.063	0.260
Productivity (C2)	**0.168**	
Production capacity	0.045	0.268
Machine performance	0.07	0.414
Technical capacity	0.028	0.164
Product design	0.026	0.154
Service level (C3)	**0.096**	
Customer service	0.038	0.396
Lead time	0.024	0.250
Flexibility	0.034	0.354
Commercial policy (C4)	**0.089**	
Commercial terms	0.04	0.453
Experience in the market	0.014	0.161
E-business	0.034	0.387
Product presentation (C5)	**0.074**	
Packaging	0.03	0.408
Cleaning conditions	0.025	0.334
Coordinated delivery	0.019	0.258
Innovation (C6)	**0.124**	
Capability of R&D	0.062	0.5
IT infrastructure	0.062	0.5
Supplier location (C7)	**0.083**	
Financial performance (C8)	**0.123**	
Price competitiveness	0.038	0.310
Financial position	0.053	0.435
Payment deadline	0.031	0.255

Note. FAHP = fuzzy analytic hierarchy process.

$$WG_c = \begin{matrix} \\ P_1 \\ P_2 \\ P_3 \\ \vdots \\ P_m \end{matrix} \begin{bmatrix} S_1 & S_2 & \cdots & S_n \\ x_{11} & x_{12} & \cdots & r_{1n} \\ x_{21} & x_{22} & \cdots & r_{2n} \\ x_{31} & x_{32} & \cdots & r_{3n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & r_{mn} \end{bmatrix}^{*} \begin{bmatrix} NG_1 \\ NG_2 \\ NG_3 \\ \vdots \\ NG_n \end{bmatrix} \quad (28)$$

TABLE 6 Consistency values for FAHP decision matrixes

Matrix	Consistency ratio (CR)
Factors	**0.043**
Quality	**0.074**
Productivity	**0.045**
Service level	**0.070**
Commercial policy	**0.003**
Product presentation	**0.017**
Innovation	**0.000**
Financial performance	**0.030**

Note. FAHP = fuzzy analytic hierarchy process.

The normalized direct-relation matrixes derive from *Z*. An illustrative example of initial and normalized relation matrixes (DEMATEL) is described in Tables 7 and 8, respectively. Afterward, WF_c and WG_c values were calculated and computed in Table 9.

On the other hand, the global contributions of criteria were graphed in Figure 5. By analysing this bar diagram, it can be noted that FINANCIAL PERFORMANCE is the most relevant criterion ($NF = 19.9\%$) when selecting providers of HDPE for this particular company. Nevertheless, there is not a big difference (13.4%) between this factor and the last in the ranking (SUPPLIER LOCATION). This indicates that the providers must satisfy criteria with almost equal contributions; therefore, their efforts should be focused on designing multicriteria strategies ensuring fruitful supplier–customer collaborations. Additionally, these results demonstrate that the company is interested in selecting providers having a variety of strengths that highly support its corporate competitive plans.

Considering the results from “Quality” cluster (refer to Figure 6a), “PRODUCT WITH SAFETY DATA” was selected as the most important subcriterion (34.7%). However, there is a non-significant gap between this element and “APPROVED PRODUCT” (31.7%). This signifies that all the subcriteria are equally relevant for the company. This is because these elements represent mandatory regulations that must be fulfilled by the manufacturer. In “Productivity” category (refer to Figure 6b), “TECHNICAL CAPACITY” was chosen as the most relevant subfactor (28.9%). Although there is a slight difference between this subcategory and the others, TECHNICAL CAPACITY was preferred due to this

TABLE 7 Initial relation matrix for “Productivity” cluster

	S4	S5	S6	S7
S4	0	3.25	3	2.75
S5	3.5	0	1.75	2.25
S6	3.25	3.5	0	2.5
S7	3	3	2.5	0

TABLE 8 Normalized direct-relation matrix for “Productivity” cluster

	S4	S5	S6	S7
S4	0	0.333	0.413	0.366
S5	0.359	0	0.241	0.3
S6	0.333	0.359	0	0.333
S7	0.307	0.307	0.344	0

TABLE 9 Local and global contributions of criteria and subcriteria by using FAHP–DEMATEL

Cluster	GW	LW
Quality (C1)	**0.131**	
FDA certificate	0.044	0.336
Product with safety data	0.045	0.346
Approved product	0.041	0.317
Productivity (C2)	**0.127**	
Production capacity	0.033	0.262
Machine performance	0.023	0.182
Technical capacity	0.037	0.289
Product design	0.034	0.266
Service level (C3)	**0.148**	
Customer service	0.045	0.304
Lead time	0.059	0.396
Flexibility	0.044	0.299
Commercial policy (C4)	**0.098**	
Commercial terms	0.023	0.237
Experience in the market	0.045	0.463
E-business	0.029	0.3
Product presentation (C5)	**0.084**	
Packaging	0.034	0.409
Cleaning conditions	0.031	0.365
Coordinated delivery	0.019	0.225
Innovation (C6)	**0.145**	
Capability of R&D	0.072	0.5
IT infrastructure	0.072	0.5
Supplier location (C7)	**0.064**	
Financial performance (C8)	**0.199**	
Price competitiveness	0.079	0.4
Financial position	0.061	0.306
Payment deadline	0.058	0.294

Note. FAHP = fuzzy analytic hierarchy process; DEMATEL = decision-making trial and evaluation laboratory.

critical to satisfaction influences the quality of the plastic bags and pipes manufactured by the company. Therefore, this variable must be controlled and monitored in order to ensure high customer satisfaction.

Taking into account the outcomes of "Service level" criterion (refer to Figure 7a), it can be observed that "LEAD TIME" (39.6%) represents the highest preference. Even though there are no significant differences among the decision elements of this cluster, LEAD TIME represents another critical to satisfaction for customers. Extended delivery periods diminish the company's response capacity to provide their products faster. This makes the company less competitive and, subsequently, less profitable. Another cluster is "Commercial policy" (refer to Figure 7b). In this category, EXPERIENCE IN THE MARKET contributes almost 50% of the total criterion weight. In this sense, the company looks for experienced HDPE suppliers due to their influence on customer satisfaction. These suppliers are more likely to avoid product safety and liability problems, which are beneficial when increasing firm performance.

The outcomes derived from the analysis of "Product presentation" (refer to Figure 8a) show that PACKAGING (40.9%) is the most influential subfactor in this cluster. Being aware of the importance of reducing the presence of impurities and contaminants in HDPE, the decision makers expressed the need of selecting providers with appropriate packaging materials that avoid potential deterioration and oxidation processes. On the other hand, both subfactors in "Innovation" factor (refer to Figure 8b) were considered as equally important; thus, the prospective suppliers should focus on developing R&D capabilities combined with IT infrastructure in order to ensure innovative products continuously.

Based on the results of the "Financial performance" category, the most significant subcriterion is PRICE COMPETITIVENESS (40%) and is also the most important when selecting HDPE suppliers (refer to Figure 9). Most of the companies aim to increase profitability and ensure future sustainability; thus, low-cost suppliers may appear to be an attractive choice to achieve this goal. Even though the managers have identified other relevant attributes for supplier selection, the low-cost provider continues to be selected in actual practice.

- Differences between perceptions of experts in AHP and DEMATEL

The differences between the participants' judgments (Quality "Q", Production "P", Management "M", and Logistics "L") for both FAHP and DEMATEL techniques were evaluated by performing correlation tests and principal factor analyses (α level = 0.05). By using XLSTAT® 2017 software, the Spearman correlation coefficients and p values were computed. Table 10 presents the results of the aforementioned comparison tests for "factors" cluster in AHP. It can be observed that all

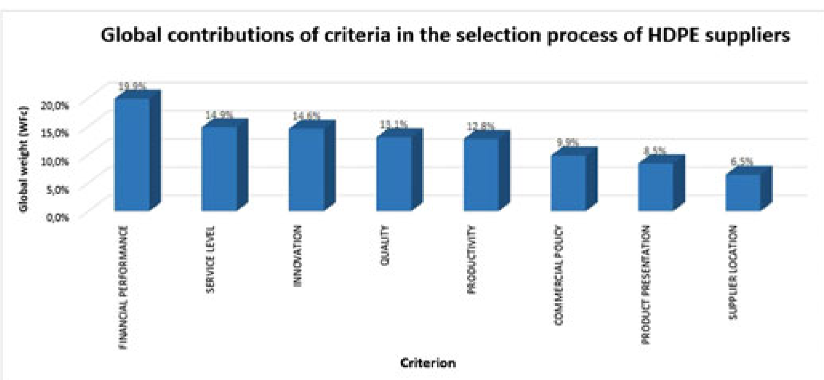

FIGURE 5 Global contributions of criteria. HPDE = high-density polyethylene

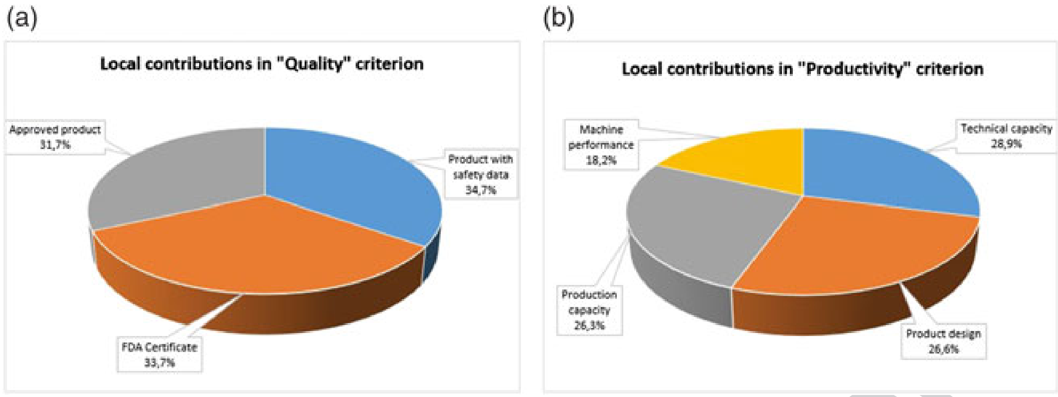

FIGURE 6 Local contributions for factors (a) Quality and (b) Productivity

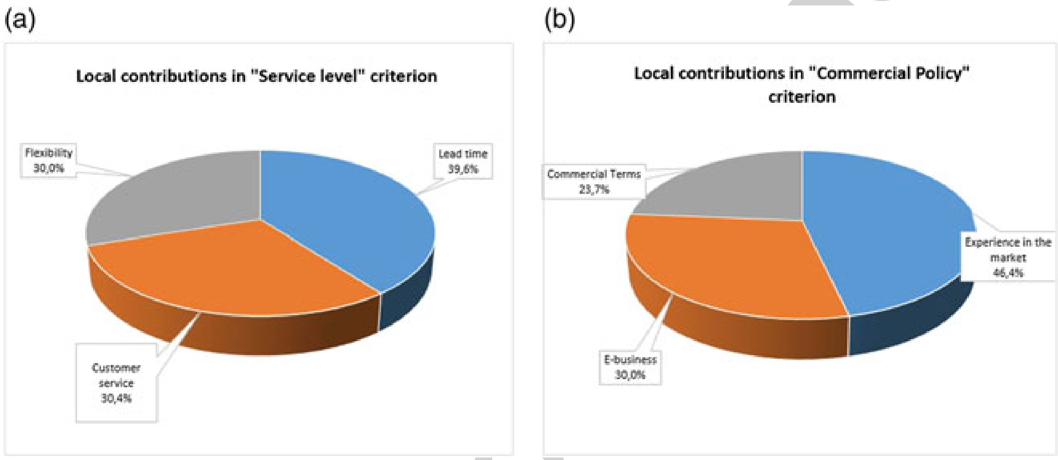

FIGURE 7 Local contributions for factors (a) Service level and (b) Commercial policy

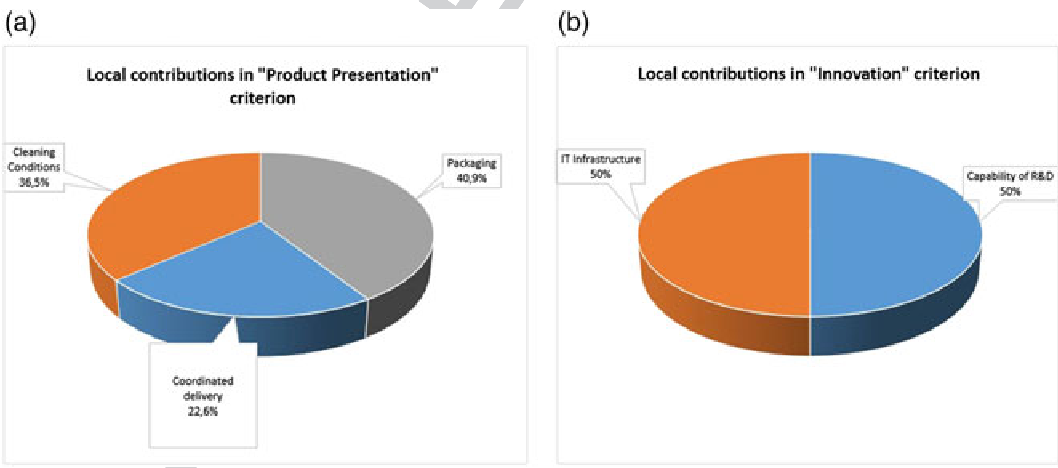

FIGURE 8 Local contributions for factors (a) Product presentation and (b) Innovation

the *p* values were found to be higher than α; therefore, the judgments were concluded not to be correlated (r = 0). This is confirmed by the Spearman correlation coefficients, which appeared to be very low. Consequently, the rankings between the departments associated with the company were weakly and poorly correlated.

However, when analysing the correlations between the pairwise judgments of participants in DEMATEL method (refer to Table 11), all the *p* values were observed to be lower than alpha level; thus, the correlations were concluded to be significant. In addition, the highest correlation was detected in "Q versus P" comparison (ρ = 0.661), which appears to be rational given the close relation between these departments. Therefore, the interdependency values derived from each participant department are significantly correlated.

5.3 | Phase 3: Interdependence between factors and subfactors using DEMATEL

The inner dependencies were evaluated via applying DEMATEL method. In this respect, the total-relation matrixes *T* were obtained

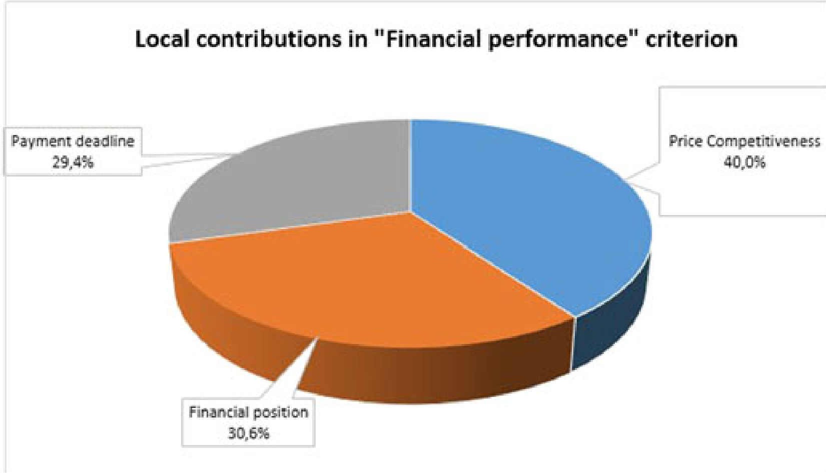

FIGURE 9 Local contributions for "Financial performance" factor

TABLE 10 Differences between participant's judgments for factors in AHP

Pairwise comparison	Spearman correlation coefficient	*p* value
F vs. Q	0.049	.803
F vs. P	0.285	.142
F vs. M	0.271	.163
Q vs. P	0.347	.071
Q vs. M	−0.175	.370
P vs. M	0.154	.431

Note. AHP = analytic hierarchy process.

TABLE 11 Differences between participant's judgments for factors in DEMATEL

Pairwise comparison	Spearman correlation coefficient	*p* value
F vs. Q	0.636	0
F vs. P	0.481	0
F vs. M	0.638	0
Q vs. P	0.661	<.0001
Q vs. M	0.501	0
P vs. M	0.394	.003

Note. DEMATEL = decision-making trial and evaluation laboratory.

by performing Equation 11. An example of this matrix is described in Table 12. Then, by using Lenth's method described in Section 3.3. The median (1.713) was selected from the total-relation matrix *T*. The initial value S_o was calculated as follows (refer to Equation 15):

$$S_o = 1.5^{*}1.713 = 2.569.$$

Using Equation 16, after the values in the total-relation matrix *T* that were greater or equal to $2.5S_o$ have been eliminated, the median (1.713) was obtained and *PSE* was computed as follows:

TABLE 12 Total-relation matrix for "Productivity" factor

	S4	S5	S6	S7
S4	1.827	2.070	1.678	1.705
S5	1.852	1.579	1.412	1.479
S6	2.115	2.122	1.473	1.720
S7	1.982	1.974	1.585	1.421

$$PSE = 1.5^{*}1.713 = 2.569.$$

Finally, using Equation 17, given α = 0.05 and *df* (degrees of freedom) = 15, it was calculated that $t_{1-\frac{\alpha}{2};\frac{m}{3}} = 2.1314$ and $ME = 2.1314^{*}2.569 = 5.4774$. An effect lower than 5.4774 was classified as non-significant. In this case, no causal relationships were found in the entire decision-making model. On the other hand, *D* + *R* and *D* − *R* values were obtained to identify the *dispatchers* and *receivers* in the hierarchy (refer to Table 13). From this table, it can be induced that, from those dimensions with positive *D* − *R* values, *Innovation* has the highest positive *D* + *R* value, which suggests that it is the largest net generator of effects and it is the most influencing parameter when selecting suppliers of HDPE. Therefore, *Innovation* should be a priority for implementation or improvement. *Financial performance*, *Quality*, and *Productivity* also have a high *D* + *R* value but its *D* − *R* is negative, meaning these categories have a large effect on the supplier selection process, yet also affected by the other criteria. Thus, these categories are *receivers* and must be classified lower in management priority.

5.4 | Phase 4: TOPSIS approach

To illustrate the implementation of TOPSIS method in this case study, a set of key performance indexes was assigned to measure the decision subcriteria of each HDPE supplier. These indexes were defined taking into account the pertinent scientific literature and the company's balanced scorecard. The description of each variable is described as follows:

- Subcriterion (S1): *FDA certificate*
  Indicator: Status of FDA certificate
  Operational definition: Assign "0" if the company does not have FDA certificate; otherwise, assign "1".
- Subcriterion (S2): *Product with safety data*
  Indicator: Presence of safety data
  Operational definition: Assign "0" if the company does not have safety data related to HDPE; otherwise, assign "1".
- Subcriterion (S3): *Approved product*
  Indicator: HDPE approval

Q12 **TABLE 13** $D - R$ and $D + R$ values of criteria and subcriteria

Factor/subfactor	$D + R$	$D - R$	Dispatcher	Receiver
Quality (C1)	5.348	−0.065		X
FDA certificate	20.667	1.333	X	
Product with safety data	21.333	0.667	X	
Approved product	20.000	−2.000		X
Productivity (C2)	5.243	−0.184		X
Production capacity	15.060	−0.496		X
Machine performance	14.072	−1.423		X
Technical capacity	13.582	1.282	X	
Product design	13.292	0.636	X	
Service level (C3)	5	0.387	X	
Customer service	12.324	−0.895		X
Lead time	12.139	0.170	X	
Flexibility	11.120	0.725	X	
Commercial policy (C4)	3.965	−0.285		X
Commercial terms	9.874	−1.352		X
Experience in the market	10.281	−0.033		X
E-business	9.402	1.384	X	
Product presentation (C5)	3.129	−0.340		X
Packaging	4.835	0.795	X	
Cleaning conditions	4.416	0.053	X	
Coordinated delivery	3.698	−0.848		X
Innovation (C6)	5.060	0.249	X	
Capability of R&D	41	−1		X
IT infrastructure	41	1	X	
Supplier location (C7)	2.803	0.169	X	
Financial performance (C8)	6.496	−0.010		X
Price competitiveness	13.665	0.065	X	
Financial position	13.200	1.200	X	
Payment deadline	12.335	−1.265		X

Operational definition: Assign "0" if the product is not approved; otherwise, assign "1".

- Subcriterion (S4): *Production capacity*
  Indicator: Annual installed capacity
  Operational definition: Installed capacity/month * 12.
- Subcriterion (S5): *Machine performance*
  Indicator: Average efficiency of the machines used in the production process
  Operational definition: $\sum_{j=1}^{m} E_j/m$,

  where m is the number of machines and E_j is the efficiency of the machine j.

- Subcriterion (S6): *Technical capacity*
  Indicator: Theoretical performance of HDPE
  Operational definition: The amount of HDPE (kg) used to produce a linear meter of plastic bags.
- Subcriterion (S7): *Product design*
  Indicator: Technical adequacy of the design
  Operational definition: Assign "0" if the product design is appropriate for the production process; otherwise, assign "1".
- Subcriterion (S8): *Customer service*
  Indicator: Average response time to resolve complaint
  Operational definition: $\frac{\sum_{t=1}^{n} ti}{n}$,

  where ti is the response time to resolve a complaint and n is the number of complaints.

- Subcriterion (S9): *Lead time*
  Indicator: Average lead time
  Operational definition: $\frac{\sum_{l=1}^{n} li}{n}$,

  where li is the order lead time and n is the number of orders.

- Subcriterion (S10): *Flexibility*
  Indicator: Number of HDPE-based products offered by the supplier
  Operational definition: Number of HDPE-based products.
- Subcriterion (S11): *Commercial terms*
  Indicator: Time to establish a commercial supplier-customer agreement
  Operational definition: Time between the commercial agreement request and the time in which it is signed.
- Subcriterion (S12): *Experience in the market*
  Indicator: Supplier age
  Operational definition: The length of time a particular supplier has been in the market.
- Subcriterion (S13): *E-business*
  Indicator: Capability in E-business
  Operational definition: Assign "0" if it is not possible to develop a relationship with the supplier by internet; otherwise, assign "1".
- Subcriterion (S14): *Packaging*
  Indicator: Packaging status
  Operational definition: Assign "0" if the package protects HDPE from oxidation; otherwise, assign "1".
- Subcriterion (S15): *Cleaning conditions*
  Indicator: Cleaning status
  Operational definition: Assign "0" if the product is not free of contaminants and impurities; otherwise, assign "1".
- Subcriterion (S16): *Coordinated delivery*
  Indicator: Average delay time
  Operational definition: $\sum_{i=1}^{n} (c_i - d_i)/n$,

  where n is the number of orders, c_i represents the completion time of the order i, and d_i is the delivery time.

- Subcriterion (S17): *Capability of R&D*
  Indicator: Capability of R&D
  Operational definition: Assign "1" if the supplier has a R&D department; otherwise, assign "0".
- Subcriterion (S18): *IT infrastructure*
  Indicator: Number of core processes with technological support
  Operational definition: Determine the number of core process having technological support. The processes under consideration are Customer service, Order tracking, and Production.

- Subcriterion (S19): *Price competitiveness*
  Indicator: Price per kilogram of HDPE
  Operational definition: Price per kilogram of HPDE (measured in COP/kg).
- Subcriterion (S20): *Financial position*
  Indicator: Working capital
  Operational definition: Current assets − Current liabilities.
- Subcriterion (S21): *Payment deadline*
  Indicator: Payment terms
  Operational definition: *Payment terms* (*measured in days*) *= Invoice due date − Invoice date*.
- Criterion (C7): *Supplier location*
  Indicator: Distance (km)
  Operational definition: Physical distance between the parties involved in the supplier–customer relationship (measured in kilometres).

Once the key performance indexes were defined, the decision matrix *X* was established with five HDPE suppliers (P1, P2, P3, P4, and P5), 21 subfactors, and 1 factor (refer to Table 14). Afterward, the subcriteria values were computed and additionally, the ideal (C^+) and anti-ideal (C^-) scenarios were defined. On the other hand, Table 15 presents the normalized decision matrix *R* that was calculated via using Equations 19–20. Then, the weighted normalized decision matrix *V* was obtained by applying Equation 21 (refer to Table 16). Based on these results, the separations of each HDPE supplier from the ideal (refer to Table 17) and anti-ideal scenarios (refer to Table 18) were calculated by using Equations 24–25, respectively. In addition, Tables 17, 18 describe the contribution of each subcriterion to d_i^+ and d_i^- correspondingly. Finally, the closeness coefficients of HDPE providers were determined via applying Equation 26 (refer to Figure 9).

Considering the results from Figure 10, it can be observed that P1 achieved the first place with the maximum score (CC = 1), which demonstrates that all its subcriteria correspond to the ideal scenario. On the other hand, P5 obtained the lowest closeness coefficient (CC = 0); therefore, it is equal to the anti-ideal scenario. Furthermore, there is a significant gap (0.9039) between P1 (first place) and P4 (second place). In this regard, the subfactors contributing mostly to d_4^+ were S9 (*Lead time*), C7 (*Supplier location*), S19 (*Price competitiveness*), S20 (*Financial position*), and S21 (*Payment deadline*). These considerations suggest that P4 must improve its financial performance to be more attractive to the company. This is due to the importance of this factor (NF = 19.9%) when selecting suppliers of HDPE. Additionally, *Lead time* is the fourth most relevant subcriterion; thus, P4 must implement shorter delivery times to support the company's operations and allow on-time product delivery. Further analysis of the distances from the anti-ideal scenario indicates that the most representative subfactors are S8 (*Customer service*), S10 (*Flexibility*), and S16 (*Coordinated delivery*). Firstly, *Customer service* is another pivotal parameter (NG = 4.5%) that must be considered by P4 due to the relevance of providing shorter times to respond the company's complaints. This is critical to efficiently control monthly production and ensure the compliance of customer request dates. It is also worthy of note that shortening delivery delays positively affects the factory performance, helps to reduce

TABLE 14 TOPSIS decision matrix for the selection of HDPE suppliers

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	C7	S19	S20	S21
P1	1	1	1	500,000	100%	100%	1	3	24	3	1	20	1	0	1	1	1	3	135.0	5398.0	419,647,087,000.00	0
P2	1	1	1	510,000	100%	100%	1	0.003472	7	4	1	20	1	0	1	1	1	3	3.8	5414.5	411,206,000.00	30
P3	0	0	1	180,000	80%	100%	1	0.006944	0.5	2	1	6	1	0	1	0	0	2	1.0	5100.0	200,000,000.00	8
P4	1	1	1	1,000,000	100%	100%	1	3	24	2	1	20	1	0	1	1	1	3	5.1	5445.5	40,381,564,700.00	0
P5	0	0	1	120,000	60%	100%	1	0.003472	2	1	1	10	1	0	1	0	0	3	1.5	5050.0	70,000,000.00	15
A+	1	1	1	1,000,000	100%	100%	1	0.003472	0.5	4	1	20	1	0	1	0	1	3	1.0	5050.0	419,647,087,000.00	30
A-	0	0	1	120,000	60%	100%	1	3	24	1	1	6	1	0	1	1	0	2	135.0	5445.5	70,000,000.00	0
W	0.044	0.045	0.041	0.034	0.023	0.037	0.034	0.045	0.059	0.045	0.023	0.046	0.03	0.035	0.031	0.019	0.073	0.073	0.065	0.08	0.061	0.059

Note. HPDE = high-density polyethylene; TOPSIS = technique for order of preference by similarity to ideal solution.

TABLE 15 Normalized TOPSIS decision matrix for the selection of HDPE suppliers

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	C7	S19	S20	S21
P1	2	2	2.449	799,515, 478,274	2.24	2.45	2.449	12.72795	833.3	21.21	2.449	833.3	2	0	2	2	2	21	18247.3	69,364,548.8	249,624, 148,173, 991,000, 000,000.00	0
P2	2	2	2.449	815,505, 787,840	2.24	2.45	2.449	0.014731	243	28.28	2.449	833.3	2	0	2	2	2	21	513.6	69,576,574.6	244,603, 026,337, 782,000, 000.00	1371
P3	0	0	2.449	287,825, 572,179	1.79	2.45	2.449	0.029463	17.36	14.14	2.449	250	2	0	2	0	0	14	135.2	65,535,235.1	118,968, 607,626, 242,000, 000.00	366
P4	2	2	2.449	1,599,030, 956,548	2.24	2.45	2.449	12.72795	833.3	14.14	2.449	833.3	2	0	2	2	2	21	699.3	69,974,926.0	24,020, 692,630, 639,900, 000,000.00	0
P5	0	0	2.449	191,883, 714,786	1.34	2.45	2.449	0.014731	69.44	7.071	2.449	416.7	2	0	2	0	0	21	202.7	64,892,732.8	41,639, 012,669, 184,600, 000.00	686
A+	2	2	2.449	1,599, 030,956, 548	2.24	2.45	2.449	0.014731	17.36	28.28	2.449	833.3	2	0	2	0	2	21	135.2	64,892,732.8	249,624, 148,173, 991,000, 000,000.00	1371
A-	0	0	2.449	191,883, 714,786	1.34	2.45	2.449	12.72795	833.3	7.071	2.449	250	2	0	2	2	0	14	18247.3	69,974,926.0	41,639, 012,669, 184,600, 000.00	0
W	0.044	0.045	0.041	0.034	0.023	0.037	0.034	0.045	0.059	0.045	0.023	0.046	0.03	0.035	0.031	0.019	0.073	0.073	0.065	0.08	0.061	0.059

Note. HPDE = high-density polyethylene; TOPSIS = technique for order of preference by similarity to ideal solution.

TABLE 16 Weighted normalized decision matrix for the selection of HDPE suppliers

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	C7	S19	S20	S21
P1	0.088	0.09	0.1	27,183,526,261	0.05	0.09	0.083266	0.5728	49.164	0.9546	0.056327	38.332	0.073	0	0.076	0.033	0.146	2	1186.1	5549163.9	15,227, 073,038,613, 500,000, 000.00	0
P2	0.088	0.09	0.1	27,727,196,787	0.05	0.09	0.083266	0.0007	14.339	1.2728	0.056327	38.332	0.073	0	0.076	0.033	0.146	2	33.4	5566126.0	14,920, 784,606, 604,700, 000.00	81
P3	0	0	0.1	9,786,069,454	0.04	0.09	0.083266	0.0013	1.024	0.6364	0.056327	11.5	0.073	0	0.076	0.000	0.000	1	8.8	5242818.8	7,257 ,085,065, 200,740, 000.00	22
P4	0.088	0.09	0.1	54,367,052,523	0.05	0.09	0.083266	0.5728	49.164	0.6364	0.056327	38.332	0.073	0	0.076	0.033	0.146	2	44.8	5597994.1	1,465, 262,250, 469,040, 000,000.00	0
P5	0	0	0.1	6,524,046,303	0.03	0.09	0.083266	0.0007	4.097	0.318195	0.056327	19.166	0.073	0	0.076	0.000	0.000	2	13.2	5191418.6	2,539, 979,772, 820,260, 000.00	40
A+	0.088	0.09	0.1	54,367,052,523	0.05	0.09	0.083266	0.0007	1.024	1.2728	0.056327	38.332	0.073	0	0.076	0.000	0.146	2	8.8	5191418.6	15,227, 073,038, 613,500, 000,000.00	81
A−	0	0	0.1	6,524,046,303	0.03	0.09	0.083266	0.5728	49.164	0.318195	0.056327	11.5	0.073	0	0.076	0.033	0.000	1	1186.1	5597994.1	2,539, 979,772, 820,260, 000.00	0

Note. HPDE = high-density polyethylene.

TABLE 17 Separations from the ideal scenario

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	C7	S19	S20	S21	Si+
P1	0.000	0.000	0.000	7.E+20	0.000	0.000	0.000	0.327	2317.432	0.101	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	1386014.348	127,981,687,601.203	0.00E+00	6544.6281	27183526263.7
P2	0.000	0.000	0.000	7.E+20	0.000	0.000	0.000	0.000	177.296	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	605.166	140,405,593,622.984	2.31E+44	0.0000	1521215225400690000000.0
P3	0.008	0.008	0.000	2.E+21	0.000	0.000	0.000	0.000	0.000	0.405	0.000	719.982	0.000	0.000	0.000	0.000	0.021	0.261	0.000	2,641,978,952.000	2.32E+44	3519.5556	1521981595354830000000.0
P4	0.000	0.000	0.000	0.E+00	0.000	0.000	0.000	0.327	2317.432	0.405	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	1297.555	165,303,603,266.631	1.89E+44	6544.6281	1376181078814440000000.0
P5	0.008	0.008	0.000	2.E+21	0.000	0.000	0.000	0.000	9.442	0.911	0.000	367.338	0.000	0.000	0.000	0.000	0.021	0.000	19.297	0.000	2.32E+44	1636.1570	1522453305884070000000.0

TABLE 18 Separations from the anti-ideal scenario

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	C7	S19	S20	S21	Si-
P1	0.0077	0.0081	0.0000	4.2681. E+20	0.0004	0.0000	0.0000	0.0000	0.0000	0.4050	0.0000	719.9817	0.0000	0.0000	0.0000	0.0000	0.0213	0.2611	0.0000	2384836004.1800	2.3179E +44	0.0000	1522453305884070000000.0
P2	0.0077	0.0081	0.0000	4.4957. E+20	0.0004	0.0000	0.0000	0.3273	1212.7438	0.9113	0.0000	719.9817	0.0000	0.0000	0.0000	0.0000	0.0213	0.2611	1328696.5256	1015576709.1487	1.5328. E+38	6544.6281	12380804833784400000.0
P3	0.0000	0.0000	0.0000	1.0641. E+19	0.0001	0.0000	0.0000	0.3265	2317.4318	0.1013	0.0000	0.0000	0.0000	0.0000	0.0000	0.0011	0.0000	0.0000	1386014.3478	126149475197.9910	2.2251. E+37	465.3958	4717105292380480000.0
P4	0.0077	0.0081	0.0000	2.2890. E+21	0.0004	0.0000	0.0000	0.0000	0.0000	0.1013	0.0000	719.9817	0.0000	0.0000	0.0000	0.0000	0.0213	0.2611	1302496.0996	0.0000	2.1396. E+42	0.0000	1462722270696220000000.0
P5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.3273	2031.0312	0.0000	0.0000	58.7740	0.0000	0.0000	0.0000	0.0011	0.0000	0.2611	1375690.2545	165303603266.6310	0.0000	1636.1570	406577.2

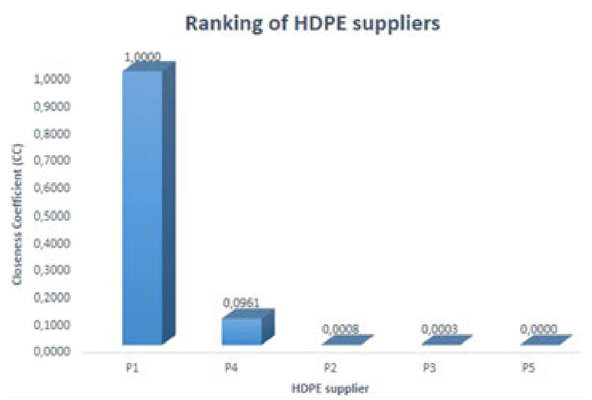

FIGURE 10 Closeness coefficients of potential high-density polyethylene (HDPE) supplier

the variability in scheduling, and avoids potential sanctions and complaints. Therefore, the supplier should increase the efficiency of its processes in order to respond directly to the company's expectations. Additionally, this supplier should design flexible production systems to face the continuous changes in customer expectations. Because *Flexibility* is a *receiver* factor, the supplier will simultaneously affect other relevant elements that may increase its closeness coefficient and ensure satisfactory performance during potential supplier–customer relationships.

6 | CONCLUSIONS

Supplier selection is an important process for the supply chain management of companies from the plastic sector. However, the studies directly concentrating on supplier selection with the use of MCDM techniques in plastic companies are largely limited. In addition, there are no specific applications on the selection of HDPE providers. Therefore, this research proposed a hybrid multiple criteria decision-making method to appropriately select suppliers of HDPE based on FAHP, DEMATEL, and TOPSIS methods. This approach is useful for managers to increase the competitiveness and sustainability performance of their organizations.

In a *decision-making* process, the experts are unable to express their judgments exactly in numerical values due to human vagueness. In order to deal with such problem, FAHP was implemented to represent imprecise data and determine linear dependencies in the hierarchy. This method was combined with DEMATEL to also evaluate interdependencies between factors and subfactors and determine potential improvement strategies. After this, TOPSIS was applied to rank the suppliers based on the global weights provided by AHP–DEMATEL and a set of indicators established with the support of the pertinent scientific literature and the company's balance scorecard. That is to say, this paper provides an efficient and precise approach that can also be used to address other managerial decision-making problems containing many criteria with vague interrelationships. Thus, it is scalable and adaptable in any reality.

Regarding the scenario under study, the results are extremely useful for managers due to the huge impact that raw material has over the total cost in companies from the plastic sector. Furthermore, productivity is also related to the quality level of HDPE. Poor supplier quality is associated with increasingly maintenance costs, machine stops, lower machine speed, and greater energy consumption. On the other hand, an unreliable HDPE supplier may force to increase safety inventory levels. All these aspects negatively affect the company financial performance. Therefore, a proper selection of HDPE suppliers is a cornerstone of the company success.

In this regard, it was found that P1 has the highest closeness coefficient and therefore, it must be selected as a supplier of HDPE. The findings also demonstrated that *Financial performance* (NF = 19.9%) is the most relevant criterion when selecting suppliers. Nonetheless, the HDPE provider must create multicriteria strategies because there are big gaps between this parameter and the others. Additionally, *Innovation* was categorized as the *receiver* with the highest positive $D + R$ value (5.060), which suggests that it is the largest net generator of effects and is the most influencing factor when selecting suppliers of HDPE. Therefore, *Innovation* should be a priority for implementation or improvement. On the other hand, it can be highlighted that the reduced 5-point scale used for FAHP was useful for reducing inconsistencies, due to the increase in significance to decision makers who are not skilled in complex mathematics or with the FAHP method.

Furthermore, future studies aim to investigate the performance of other powerful hybrid MCDM methods including ANP, PROMETHEE, and ELECTRE. These methods can be used to compare the approach proposed in this paper in order to identify prospective methodological improvements. On the other hand, future investigations may consider environmental parameters to support green supply chain management practices.

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REFERENCES

Alimardani, M., Rabbani, M., & Rafiei, H. (2014). A novel hybrid model based on DEMATEL, ANP and TOPSIS for supplier selection in agile supply chains. *International Journal of Services and Operations Management*, *18*(2), 179–211.

Ar, I. M., Göksen, H., & Tuncer, M. A. (2015). Kablo Sektöründe Tedarikçi Seçimi Için Bütünlesik DEMATEL-AAS-VIKOR Yönteminin Kullanilmasi/using integrated DEMATEL-ANP-VIKOR method for supplier selection in cable sector. *Ege Akademik Bakis*, *15*(2), 285.

Ayhan, M. B. (2013). A fuzzy AHP approach for supplier selection problem: A case study in a gear motor company. *arXiv preprint arXiv*:1311.2886.

Azar, G., & Drogendijk, R. (2014). Psychic distance, innovation, and firm performance. *Management International Review*, *54*(5), 581–613.

Barrios, M. A. O., De Felice, F., Negrete, K. P., Romero, B. A., Arenas, A. Y., & Petrillo, A. (2016). An AHP-TOPSIS integrated model for selecting the most appropriate tomography equipment. *International Journal of Information Technology & Decision Making*, *15*(4), 861–885.

Chai, J., Liu, J. N., & Ngai, E. W. (2013). Application of decision-making techniques in supplier selection: A systematic review of literature. *Expert Systems with Applications*, *40*(10), 3872–3885.

Chamodrakas, I., Leftheriotis, I., & Martakos, D. (2011). In-depth analysis and simulation study of an innovative fuzzy approach for ranking alternatives in multiple attribute decision making problems based on TOPSIS. *Applied Soft Computing*, *11*(1), 900–907.

Chan, F. S. (2003). Interactive selection model for supplier selection process: An analytical hierarchy process approach. *International Journal of Production Research*, *41*(15), 3549–3579.

Chen, C. T., Lin, C. T., & Huang, S. F. (2006). A fuzzy approach for supplier evaluation and selection in supply chain management. *International Journal of Production Economics*, *102*(2), 289–301.

Daim, T. U., Udbye, A., & Balasubramanian, A. (2013). Use of analytic hierarchy process (AHP) for selection of 3PL providers. *Journal of Manufacturing Technology Management*, *24*(1), 28–51.

Dargi, A., Anjomshoae, A., Galankashi, M. R., Memari, A., & Tap, M. B. M. (2014). Supplier selection: A fuzzy-ANP approach. *Procedia Computer Science*, *31*, 691–700. http://doi.org/10.1016/j.procs.2014.05.317

Demirtas, E. A., & Üstün, Ö. (2008). An integrated multiobjective decision making process for supplier selection and order allocation. *Omega*, *36*(1), 76–90.

Dweiri, F., Kumar, S., Khan, S. A., & Jain, V. (2016). Designing an integrated AHP based decision support system for supplier selection in automotive industry. *Expert Systems with Applications*, *62*, 273–283.

Dymova, L., Sevastjanov, P., & Tikhonenko, A. (2013). A direct interval extension of TOPSIS method. *Expert Systems with Applications*, *40*(12), 4841–4847.

Ertuğrul, İ., & Karakaşoğlu, N. (2009). Performance evaluation of Turkish cement firms with fuzzy analytic hierarchy process and TOPSIS methods. *Expert Systems with Applications*, *36*(1), 702–715.

Florez Piña, L. (2013). Ejecución de un protocolo para la selección de proveedores de una poliolefina de alta densidad. Universidad de Costa Rica.

Forum, W. E. (Ed) (2016). *The New Plastics Economy Rethinking the future of plastics*. Geneva: Switzerland.

Ho, W., Xu, X., & Dey, P. K. (2010). Multi-criteria decision making approaches for supplier evaluation and selection: A literature review. *European Journal of Operational Research*, *202*(1), 16–24.

Hosseini, S., & Al Khaled, A. (2016). A hybrid ensemble and AHP approach for resilient supplier selection. *Journal of Intelligent Manufacturing*, 1–22.

Hsieh, Y. F., Lee, Y. C., & Lin, S. B. (2016). Rebuilding DEMATEL threshold value: An example of a food and beverage information system. *SpringerPlus*, *5*(1), 1385.

Huizingh, E. K., & Vrolijk, H. C. (1997). A comparison of verbal and numerical judgments in the analytic hierarchy process. *Organizational Behavior and Human Decision Processes*, *70*(3), 237–247.

Hung, S. J. (2011). Activity-based divergent supply chain planning for competitive advantage in the risky global environment: A DEMATEL-ANP fuzzy goal programming approach. *Expert Systems with Applications*, *38*(8), 9053–9062.

Joshi, R., Banwet, D. K., & Shankar, R. (2011). A Delphi-AHP-TOPSIS based benchmarking framework for performance improvement of a cold chain. *Expert Systems with Applications*, *38*(8), 10170–10182.

Kannan, D., Govindan, K., & Rajendran, S. (2015). Fuzzy axiomatic design approach based green supplier selection: A case study from Singapore. *Journal of Cleaner Production*, *96*, 194–208.

Khorshidi, R., Hassani, A., Rauof, A. H., & Emamy, M. (2013). Selection of an optimal refinement condition to achieve maximum tensile properties of Al–15%Mg_2Si composite based on TOPSIS method. *Materials & Design*, *46*, 442–450.

Kilincci, O., & Onal, S. A. (2011). Fuzzy AHP approach for supplier selection in a washing machine company. *Expert Systems with Applications*, *38*(8), 9656–9664.

Kittur, J., Vijaykumar, S., Bellubbi, V. P., Vishal, P., & Shankara, M. G. (2015). Comparison of different MCDM techniques used to evaluate optimal generation. In *International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT)*, October, pp. 172-177, IEEE.

Koufteros, X., Vickery, S. K., & Dröge, C. (2012). The effects of strategic supplier selection on buyer competitive performance in matched domains: Does supplier integration mediate the relationships? *Journal of Supply Chain Management*, *48*(2), 93–115.

Kucukaltan, B., Irani, Z., & Aktas, E. (2016). A decision support model for identification and prioritization of key performance indicators in the logistics industry. *Computers in Human Behavior*, *65*, 346–358.

Lamoureux, J. F., & Evans, T. A. (2011). Supply chain finance: A new means to support the competitiveness and resilience of global value chains. Available at SSRN: https://ssrn.com/abstract=2179944 or https://doi.org/10.2139/ssrn.2179944

Lenth, R. V. (1989). Quick and easy analysis of unreplicated factorials. *Technometrics*, *31*(4), 469–473.

Lima Junior, F., Osiro, L., & Carpinetti, L. (2014). A comparison between fuzzy AHP and fuzzy TOPSIS methods to supplier selection. *Applied Soft Computing: vol*, *21*, 194–209.

Liou, J. J., Yen, L., & Tzeng, G. H. (2008). Building an effective safety management system for airlines. *Journal of Air Transport Management*, *14*(1), 20–26.

Meesariganda, B. R., & Ishizaka, A. (2017). Mapping verbal AHP scale to numerical scale for cloud computing strategy selection. *Applied Soft Computing*, *53*(April), 111–118.

Mo, H., & Deng, Y. (2016). A new aggregating operator for linguistic information based on D numbers. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, *24*(06), 831–846.

Monczka, R. M., Handfield, R. B., Giunipero, L. C., & Patterson, J. L. (2015). *Purchasing and supply chain management*Cengage Learning.

More, D., & Basu, P. (2013). Challenges of supply chain finance: A detailed study and a hierarchical model based on the experiences of an Indian firm. *Business Process Management Journal*, *19*(4), 624–647.

Nerkar, A., & Paruchuri, S. (2005). Evolution of R&D capabilities: The role of knowledge networks within a firm. *Management Science*, *51*(5), 771–785.

Orji, I., & Wei, S. (2014). A decision support tool for sustainable supplier selection in manufacturing firms. *Journal of Industrial Engineering and Management*, *7*(5), 1293–1315.

Öztayşi, B., & Uçal, I. (2009). Comparing MADM techniques for use in performance measurement. In *Proceedings of the International Symposium on the Analytic Hierarchy Process*, Pittsburgh, USA, pp. 53-64.

Paloma, M., & Ortiz, C. (2012). Presente Futuro de la Industria del Plástico en México.

Pecchia, L., Bath, P. A., Pendleton, N., & Bracale, M. (2010). Web-based system for assessing risk factors for falls in community-dwelling elderly people using the analytic hierarchy process. *Internationa Journal of the Analytic Hierarchy Process*, *2*(2).

Pecchia, L., Martin, J. L., Ragozzino, A., Vanzanella, C., Scognamiglio, A., Mirarchi, L., & Morgan, S. P. (2013). User needs elicitation via analytic hierarchy process (AHP). A case study on a computed tomography (CT) scanner. *BMC Medical Informatics and Decision Making*, *13*(2), 1–11.

Pi, W. N., & Low, C. (2006). Supplier evaluation and selection via Taguchi loss functions and an AHP. *The International Journal of Advanced Manufacturing Technology*, *27*(5–6), 625–630.

Poveda-Bautista, R., Baptista, D. C., & García-Melón, M. (2012). Setting competitiveness indicators using BSC and ANP. *International Journal of Production Research*, *50*(17), 4738–4752.

Prajogo, D., Oke, A., & Olhager, J. (2016). Supply chain processes: Linking supply logistics integration, supply performance, lean processes and competitive performance. *International Journal of Operations & Production Management*, *36*(2), 220–238.

Pulles, N. J., Pulles, N. J., Veldman, J., Veldman, J., Schiele, H., & Schiele, H. (2016). Winning the competition for supplier resources: The role of preferential resource allocation from suppliers. *International Journal of Operations & Production Management*, *36*(11), 1458–1481.

Rastar, H., Oobari, H. B., Digesarai, E. G., & Sadeghian, S. (2013). Province bank branches performance evaluation by using data envelopment analysis (DEA). *International Journal of Business and Behavioral Sciences*, *3*(5), 77–84.

Raut, R. D., Bhasin, H. V., & Kamble, S. S. (2011). Evaluation of supplier selection criteria by combination of AHP and fuzzy DEMATEL method. *International Journal of Business Innovation and Research*, *5*(4), 359–392.

Rezaeisaray, M., Ebrahimnejad, S., & Khalili-Damghani, K. (2016). A novel hybrid MCDM approach for outsourcing supplier selection: A case study in pipe and fittings manufacturing. *Journal of Modelling in Management*, *11*(2), 536–559.

Saaty, T. L. (2004). Decision making—The analytic hierarchy and network processes (AHP/ANP). *Journal of Systems Science and Systems Engineering*, *13*(1), 1–35.

Saaty, T. L. (2005). The analytic hierarchy and analytic network processes for the measurement of intangible criteria and for decision-making. In J. Figueira, S. Greco, & M. Ehrgott (Eds.), *Multiple criteria decision analysis: State of the art surveys* (pp. 345–407). Boston: Springer Science + Business Media Inc.

Saaty, T. L. (2013). The modern science of multicriteria decision making and its practical applications: The AHP/ANP approach. *Operations Research*, *61*(5), 1101–1118.

Saaty, T. L., & Vargas, L. G. (2013). *The logic of priorities: applications of business, energy, health and transportation*Springer Science & Business
Q14 Media.

Sadgrove, K. (2016). *The complete guide to business risk management*.
Q15 Routledge.

Sanders, N. R. (2007). The benefits of using E-business technology: The supplier perspective. *Journal of Business Logistics*, *28*(2), 177–207.

Santana, R. M. C., & Gondim, G. (2009). Influence of cleaning conditions on the degradation of recycled HDPE. *Journal of Applied Polymer Science*, *112*(3), 1454–1460.

Scholl, A., Manthey, L., Helm, R., & Steiner, M. (2005). Solving multiattribute design problems with analytic hierarchy process and conjoint analysis: An empirical comparison. *European Journal of Operational Research*, *164*(3), 760–777.

Shaik, M. N., & Abdul-Kader, W. (2013). Transportation in reverse logistics enterprise: A comprehensive performance measurement methodology. *Production Planning & Control*, *24*(6), 495–510.

Shanian, A., & Savadogo, O. (2006). TOPSIS multiple-criteria decision support analysis for material selection of metallic bipolar plates for polymer electrolyte fuel cell. *Journal of Power Sources*, *159*(2), 1095–1104.

Shaverdi, M., Heshmati, M. R., & Ramezani, I. (2014). Application of fuzzy AHP approach for financial performance evaluation of Iranian petrochemical sector. *Procedia Computer Science*, *31*, 995–1004. http://doi.org/10.1016/j.procs.2014.05.352

Simić, D., Kovačević, I., Svirčević, V., & Simić, S. (2016). 50 years of fuzzy set theory and models for supplier assessment and selection: A literature review. *Journal of Applied Logic*. http://doi.org/10.1016/j.jal.2016.11.016

Stević, Ž., Tanackov, I., Vasiljević, M., Novarlić, B., & Stojić, G. (2016). An integrated fuzzy AHP and TOPSIS model for supplier evaluation. *Serbian Journal of Management*, *11*(1), 15–27.

Su, C. M., Horng, D. J., Tseng, M. L., Chiu, A. S., Wu, K. J., & Chen, H. P. (2016). Improving sustainable supply chain management using a novel hierarchical grey-DEMATEL approach. *Journal of Cleaner Production*, *134*, 469–481.

Sun, C., Huang, H., & Miao, M. (2015). Collaborative decision-making method for large equipment enterprise's supplier selection with incomplete information. In *12th International Conference on Service Systems and Service Management (ICSSSM)*, June, pp. 1-5, IEEE.

Tajdini, S., & Nazari, M. (2012). IS outsourcing decision: A quantitative approach. *International Journal of Business and Management*, *7*(2), 113–129.

Upton, D. M. (1994). The management of manufacturing flexibility. *California Management Review*, *36*(2), 72–89.

Urban, G. L., Sultan, F., & Qualls, W. J. (2000). Placing trust at the center of your Internet strategy. *MIT Sloan Management Review*, *42*(1), 39.

Ustun, O., & Demirtas, E. A. (2008). An integrated multi-objective decision-making process for multi-period lot-sizing with supplier selection. *Omega*, *36*(4), 509–521.

Van Horenbeek, A., & Pintelon, L. (2014). Development of a maintenance performance measurement framework—Using the analytic network process (ANP) for maintenance performance indicator selection. *Omega*, *42*(1), 33–46.

Vázquez, H., & Dacosta, O. (2007). Fermentación alcohólica: Una opción para la producción de energía renovable a partir de desechos agrícolas. *Ingeniería, Investigación Y Tecnología*, *8*(4), 249–259.

Velasquez, M., & Hester, P. T. (2013). An analysis of multi-criteria decision making methods. *International Journal of Operations Research*, *10*(2), 56–66.

Vijayvargiya, A., & Dey, A. K. (2010). An analytical approach for selection of a logistics provider. *Management Decision*, *48*(3), 403–418.

Viloria, A. (2016). Commercial strategies providers pharmaceutical chains for logistics cost reduction. *Indian Journal of Science and Technology*,
8(1). Q16

Wang, G., Qin, L., Li, G., & Chen, L. (2009). Landfill site selection using spatial information technologies and AHP: A case study in Beijing, China. *Journal of Environmental Management*, *90*(8), 2414–2421.

Wang, C. H., & Wu, H. S. (2016). A novel framework to evaluate programmable logic controllers: A fuzzy MCDM perspective. *Journal of Intelligent Manufacturing*, *27*(2), 315–324.

Wei, P. L., Huang, J. H., Tzeng, G. H., & Wu, S. I. (2010). Causal modeling of web-advertising effects by improving SEM based on DEMATEL technique. *International Journal of Information Technology & Decision Making*, *9*(05), 799–829.

Wetzstein, A., Hartmann, E., Benton Jr., W. C., & Hohenstein, N.-O. (2016). A systematic assessment of supplier selection literature—State-of-the-art and future scope. *International Journal of Production Economics*, *182*, 304–323. http://doi.org/10.1016/j.ijpe.2016.06.022

Wood, D. A. (2016). Supplier selection for development of petroleum industry facilities, applying multi-criteria decision making techniques including fuzzy and intuitionistic fuzzy TOPSIS with flexible entropy weighting. *Journal of Natural Gas Science and Engineering*, *28*, 594–612.

Wu, W. W. (2008). Choosing knowledge management strategies by using a combined ANP and DEMATEL approach. *Expert Systems with Applications*, *35*(3), 828–835.

Wu, Q., Jia, R., & Yu, H. (2014). Study on environmental efficiency of electric power industry based on DEA optimization model. *Journal of Information & Computational Science*, *11*(3), 781–795.

Wu, C. S., Lin, C. T., & Lee, C. (2010). Optimal marketing strategy: A decision-making with ANP and TOPSIS. *International Journal of Production Economics*, *127*(1), 190–196.

Zavadskas, E. K., Govindan, K., Antucheviciene, J., & Turskis, Z. (2016). Hybrid multiple criteria decision-making methods: A review of applications for sustainability issues. *Economic Research-Ekonomska Istraživanja*, *29*(1), 857–887.

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