Gest. Prod., São Carlos, v. 26, n. 2, e3565, 2019
https://doi.org/10.1590/0104-530X-3565-19

Original Article

GESTÃO & PRODUÇÃO
ISSN 0104-530X (Print)
ISSN 1806-9649 (Online)

Supplier selection and evaluation model proposal for industrial maintenance based on Fuzzy-TOPSIS

Proposta de um modelo de avaliação e de seleção de fornecedores de manutenção industrial utilizando Fuzzy-TOPSIS

Lucas Daniel Del Rosso Calache[1]
Carolina Belotti Pedroso[1]
Francisco Rodrigues Lima Junior[2]
Luiz César Ribeiro Carpinetti[1]

How to cite: Calache, L. D. D. R., Pedroso, C. B., Lima Júnior, F. R., & Carpinetti, L. C. R. (2019). Supplier selection and evaluation model proposal for industrial maintenance based on Fuzzy-TOPSIS. *Gestão & Produção*, 26(2), e3565. https://doi.org/10.1590/0104-530X-3565-19

Abstract: The stiff competition among supply chains has created the necessity of better supplier management and development practices. This paper purposes a model to evaluate and to select suppliers for industrial maintenance by applying a multi-criteria decision-making technique to categorize alternative suppliers. Fuzzy TOPSIS technique was applied to evaluate the criteria related to costs and reliability belonging to a proposed categorization matrix. A case study was carried out in a sugar-energy company, in which the proposed evaluation and selection model was applied to check the existing agricultural machinery maintenance alternatives. The results culminated in a tool to support the decision-making process, helping companies to decide whether to make their own maintenance or to outsource them. The proposed model can contribute to the selection of industrial maintenance suppliers since it provides background for better decision making.

Keywords: Supplier evaluation; Supplier selection; Fuzzy-TOPSIS; Maintenance; Multi-criteria decision making.

Resumo: *A concorrência acirrada entre as cadeias de suprimento tem promovido a necessidade de melhores práticas de desenvolvimento e gestão de fornecedores por parte das empresas. O presente artigo busca propor um modelo de avaliação e seleção de fornecedores de manutenção industrial, através da aplicação de uma técnica de tomada de decisão multicritério a fim de categorizar as alternativas de fornecedores. A técnica Fuzzy-TOPSIS foi aplicada para avaliar os critérios referentes às dimensões de custos e confiabilidade dentro de uma matriz de categorização proposta. Realizou-se um estudo de caso em uma indústria sucroenergética, na qual o modelo de avaliação e seleção proposto foi aplicado para verificar as alternativas de manutenção para máquinas agrícolas. O resultado obtido culminou em uma ferramenta para auxiliar o processo de tomada de decisão considerando fontes internas e externas de manutenção. O modelo proposto pôde contribuir para a seleção dos fornecedores de manutenção industrial, uma vez que a avaliação realizada fornece subsídios para uma melhor tomada de decisão.*

Palavras-chave: *Avaliação de fornecedores; Seleção de fornecedores; Fuzzy-TOPSIS; Manutenção; Tomada de decisão multicritério.*

1 Introduction

Globalization is seen as a remarkable process that has been promoting an increase in global competition, raising customer demands and providing greater interaction between all stages of the supply chain. Many companies are looking for ways to gain competitive advantages over cost, service, quality, delivery time and other criteria that are essential to capture a larger market share (Liker & Choi, 2004).

[1] Departamento de Engenharia de Produção, Escola de Engenharia de São Carlos, Universidade de São Paulo – USP, Av. Trabalhador São-carlense, 400, Parque Arnold Schimidt, CEP 13566-590, São Carlos, SP, Brasil, e-mail: lucascalache@gmail.com

[2] Departamento de Gestão e Economia, Universidade Tecnológica Federal do Paraná – UTFPR, Campus Curitiba, Av. Sete de Setembro, 3165, Rebouças, CEP 80230-901, Curitiba, PR, Brasil

Received Nov. 3, 2017 - Accepted Mar. 15, 2018
Financial support: CAPES (001) and FAPESP (2016/18807-6; 2016/14618-4).

Meeting customer needs depends on the ability of managing the supply chain. Organizations must be able to add value not only at the organizational functions directly involved with value creation but also in the company as a whole. It is also very important that the company implements a range of techniques and approaches concerning the needs of the product or service specification (Hayes et al., 2008).

Maintenance management plays an important role in contributing to the competitiveness of an organization. The proper maintenance process is expected to provide several benefits, such as extending assets' life span, ensuring satisfactory availability levels to promote adequate return on investments, equipment operational readiness, avoiding assembly line stops that may cause imbalance in production scheduling, and the need to promote employees' safety (Bertolini et al., 2004).

Choosing wrong industrial maintenance suppliers can influence the organization's production process in a negative way, causing production line stops, higher costs, deterioration of service level and consequent loss of competitiveness, impacting not only the organization, but also the supply chain as a whole. Despite the importance of the topic, research that explores supplier evaluation and selection for industrial maintenance are still lacking. Thus, it is critical to provide ways to support organizations in decision-making processes regarding supplier evaluation and selection.

Fuzzy-TOPSIS is one of the most used techniques in supplier management (Pardha Saradhi et al., 2016). It is considered as one of the best MCDM methods in solving problems, due to its simplicity of application and avoiding inversion in alternatives ranking when a new alternative is inserted (Kuo et al., 2015). The goal of this research is to support decision-making process of evaluation and selection of maintenance alternatives through Fuzzy-TOPSIS technique. A practical application was carried out in a sugar-energy company in which the possibilities of vertical integration and outsourcing of agricultural machinery maintenance activities were evaluated.

The present research is structured in the following way: the first part of this paper brings the introduction; section 2 contains the literature review on industrial maintenance management. Section 3 discusses multi-criteria decision-making methods used to evaluate and select suppliers for industrial maintenance. Section 4 presents the concepts related to Fuzzy Set Theory and to Fuzzy-TOPSIS. In section 5 the proposed model is presented. Section 6 shows the application of a real case, carried out in a sugar-energy company. Finally, section 7 presents the main conclusions and suggestions for future research.

2 Literature review

2.1 Industrial maintenance management

Over the last decade there has been a trend of outsourcing and vertical disintegration, in which companies have sought to concentrate efforts on their core competencies. The choice of activities to be outsourced represents an important decision in supply chain management. Thus, skills that are not considered central are candidates for outsourcing (such as, repair of generic and common equipment, electrical and electronic parts, and reviews of productive plants) (Wang & Lv, 2015). Several maintenance activities are carried out by a growing number of specialized suppliers available in the market, with competitive costs and high quality indices and at the same time, the risk of the contracting company losing its know-how is relatively low (Bertolini et al., 2004).

Several factors favor the valuation of maintenance services, becoming a critical activity for the company's competitiveness: (i) technological changes and new management methodologies influenced by the way in which maintenance is seen. This phenomenon can be attributed mainly to management philosophies such as Just in Time that focused on reducing delivery time and improved quality (Luxhøj et al., 1997); (ii) Trends such as job enrichment and automation have led to the incorporation of information technology into products and production equipment's maintenance, leading to changes from mechanical maintenance to electronic maintenance, i.e. (Uysal & Tosun, 2012); (iii) Sociological trends, such as lack of capital, currency fluctuations, increased competition and levels of quality and environmental awareness required also contributed to the necessity of higher levels of maintenance (Tsang, 2002).

Different contexts require differentiated strategies, in which vertical integration may be more appropriate, or the option of outsourcing may be more suitable, depending on the situation under analysis. Thus, an organization should analyze the item or service candidate for this decision thoroughly, investigating its individual parts and considering the costs and risks inherent in this decision. An additional factor attributed to this methodology are the strategic issues, which cannot be measured purely in terms of production costs and delivery (Hayes et al., 2008). A multi-criteria analysis can provide a more adequate decision, taking into account several criteria that affect the performance and satisfaction of the stakeholders involved (Shafiee, 2015).

2.2 Multi-criteria decision making methods applied to industrial maintenance management

Literature on supplier evaluation and selection for industrial maintenance covers costs reduction, raising products quality level, increasing products availability and reliability, increasing the safety requirements, among others. Despite the variety of criteria involved in the process of supplier's evaluation and selection for industrial maintenance, a large part of existing research is restricted to the costs reduction (Almeida et al., 2015). Thus, it is necessary to develop formal models that involve a wide range of criteria, as pointed out by Bertolini et al. (2004): price / cost, environmental and safety performance, time performance, quality of work and quantity of work.

Almeida et al. (2015) state that the reduction of maintenance investments are not related to the maximization of reliability measures of the system nor to the reach of satisfactory values of environmental and safety criteria. It is suggested that the definition of maintenance policy should be based not only on the cost maintenance rate, but also in reliability measures. A major reason for this is the fact that different components of the system may have different maintenance costs and the reliability importance of each part of the system may be different (Almeida, 2001; Sellitto, 2005).

The main criteria used in supplier evaluation and selection for industrial maintenance are pointed out by Almeida et al. (2015). Cost is the main criterion used in supplier evaluation and selection for industrial maintenance, representing 68% of the total criteria used. Then, as the second most used criterion, reliability has been shown to be an important factor for industrial maintenance, appearing in 38% of the papers. It is important to emphasize that the concept of reliability is comprehensive and may involve other criteria that are traditionally analyzed separately, such as availability, time between failures, security, among others. The Supply Chain Operations Reference (SCOR) model considers reliability in the scope of supply chain management as a set of metrics, such as the percentage of completed deliveries, combined delivery performance, accurate documentation, perfect condition, among others. Cavalcante & Almeida (2005) present the conflict between reliability and cost: it is desired to reach the lowest value of costs while the reliability should be as large as possible.

MCDM models applied to supplier evaluation and selection for industrial maintenance can be divided into two types. The first type is the classic MCDM model, in which the classifications and criteria weights are represented by specific numbers. The other type is the Fuzzy Model MCDM (FMCDM), in which the classifications and weights of the evaluated criteria seek to represent the imprecision, or the intrinsic subjectivity of the problem, in which the imprecision is expressed through linguistic terms and then transformed into Fuzzy numbers (Shafiee, 2015).

Taking into consideration the research developed by Almeida et al. (2015), which provides a review of multi-criteria methods applied to industrial maintenance, and a complementary search conducted in Scopus and Web of Science databases, it was possible to identify the most recent research on the subject: MAUT: (Almeida, 2001; Brito et al., 2010; Monte & Almeida, 2016); AHP: (Tanaka et al., 2010; Medjoudj et al., 2013); MACBETH: (Srivastava & Mittal, 2012; Carnero & Gómez, 2016); ELECTRE: (Brito et al., 2010); PROMETHEE: (Cavalcante et al., 2010); and TOPSIS: (Shyjith et al., 2008; Kumar & Agrawal, 2009).

3 Fuzzy set theory

In this section the main concepts about the technique used in this research will be presented.

3.1 Fuzzy set theory

Decision making processes usually involves incomplete or uncertain information that needs to be translated to decision makers' preferences. Fuzzy logic proposed by Zadeh (1996) and widely consolidated in the multi-criteria models of decision-making (Abdullah, 2013), deals with imprecision modeling. Language variables are widely used to facilitate the expression of those responsible for evaluation and decision making. In Fuzzy Set Theory, the variables values are represented qualitatively by means of linguistic terms and quantitatively translated by Fuzzy sets in the discourse universe of the respective pertinence functions. A Fuzzy number is a Fuzzy set in which the membership function satisfies the conditions of normality and convexity (Zadeh, 1968; Lima & Carpinetti, 2016).

3.1.1 Basic Fuzzy definitions

Fuzzy sets: A Fuzzy set A is defined as in Equation 1:

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

In which $\mu_A(x)$: $X \rightarrow [0,1]$ is a function of the fuzzy set $\tilde{A}$ and $\mu_A(x)$ is the degree of membership of x in A. If $\mu_A(x)$ is equals 0, then x does not belong to the Fuzzy set A. If $\mu_A(x)$ is equal to 1, x belongs completely to the Fuzzy set A. However, if $\mu_A(x)$ has a value between 0 and 1, then x partially belongs to the Fuzzy set A. Thus, it can be said that the pertinence of x is true with a degree of pertinence given by $\mu_A(x)$ (Zadeh, 1996; Zimmermann, 2010).

Fuzzy Numbers: A Fuzzy Number is a Fuzzy Set in which the membership function satisfies the normality condition: $\sup \tilde{A}[x]_x \in X = 1$; and convexity: $\tilde{A}\left[\lambda x_1 + (1-\lambda) x_2 \geq \min\left[A(x_1), A(x_2)\right]\right]$ for all $x_1, x_2 \in X$ and all $\lambda \in [0,1]$. Fuzzy theory is commonly used because of its intuitive relevance function (Lima et al., 2013). Thus, $\mu_A(x)$ is given by the Equation 2:

$$\mu_A(x) = \begin{cases} 0 & \text{for } x < l, \\ \dfrac{x-a}{m-a} & \text{for } a \le x \le m, \\ \dfrac{u-x}{u-m} & \text{for } m \le x \le u, \\ 0 & \text{for } x > u. \end{cases} \tag{2}$$

Being l, m and u real numbers with $l < m < u$, in which m represents the maximum point in the degree of membership, and outside the range $[l,u]$, the degree of membership is null (Osiro et al., 2014; Zimmermann, 2010).

3.1.2 Algebraic operations with Fuzzy numbers

Given a real number K and two triangular Fuzzy numbers $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$, the main algebraic operations are presented below as in Equations 3 to 8 (Lima et al., 2013, 2014; Zimmermann, 2010).

- Addition of two triangular Fuzzy numbers:

$$\tilde{A}(+)\tilde{B} = (l_1 + l_2,\ m_1 + m_2,\ u_1 + u_2)\quad l_1 \ge 0, l_2 \ge 0 \tag{3}$$

- Multiplication of two triangular Fuzzy numbers:

$$\tilde{A}(X)\tilde{B} = (l_1 X l_2, m_1 X m_2, u_1 X u_2)\quad l_1 \ge 0, l_2 \ge 0 \tag{4}$$

- Subtraction of two triangular Fuzzy numbers:

$$\tilde{A}(-)\tilde{B} = (l_1 - l_2, m_1 - m_2, u_1 - u_2)\quad l_1 \ge 0, l_2 \ge 0 \tag{5}$$

- Division of two triangular Fuzzy numbers:

$$\tilde{A}(\div)\tilde{B} = (l_1 \div u_2, m_1 \div m_2, u_1 \div l_2)\quad l_1 \ge 0, l_2 \ge 0 \tag{6}$$

- Multiplying a triangular Fuzzy number by a constant K:

$$K \times \tilde{A} = (K \times l_1, K \times m_1, K \times u_1)\quad l_1 \ge 0, K \ge 0 \tag{7}$$

- Dividing a triangular Fuzzy number by a constant K:

$$\frac{\tilde{A}}{K} = \left(\frac{l_1}{K}, \frac{m_1}{K}, \frac{u_1}{K}\right)\quad l_1 \ge 0, K \ge 0 \tag{8}$$

3.2 Fuzzy-TOPSIS

Fuzzy TOPSIS is a multi-criteria technique developed by Chen (2000), in which the author proposes an effective method to measure the distance between two triangular Fuzzy numbers, extending the procedure commonly adopted by TOPSIS to the Fuzzy universe (Chen et al., 2006). This approach is widely used in supply chain management, contributing to supplier selection and evaluation problems (Arabzad et al., 2015; Çakır, 2016; He et al., 2016; Kuo et al., 2015; Lima & Carpinetti, 2016; Sangaiah et al., 2015; Pardha Saradhi et al., 2016; Wood, 2016).

In Fuzzy TOPSIS, the scores of the alternatives and the weight of the decision criteria are defined as linguistic variables that are evaluated by the decision makers. The followings steps are used for applying the technique, considering the decision makers D_r (r = 1, 2, ... k), that evaluate the criteria C_j (j = 1, 2, ... m) with weight W_j (j = 1, 2, ... m) to the alternatives A_i (i = 1, 2, ... n).

Step 1: Aggregation of the linguistic values provided by each decision-maker on the performance of the alternatives and the weights of the criteria using Equations 9 and 10. Büyüközkan & Arsenyan (2009), present a form of aggregation for group decision-making (Lima et al., 2014; Lima & Carpinetti, 2015).

$$\tilde{X}_{ij} = \frac{1}{K}\left[\tilde{X}_{ij}^{1} + \tilde{X}_{ij}^{r} + \ldots + \tilde{X}_{ij}^{K}\right] \tag{9}$$

$$\widetilde{W}_{ij} = \frac{1}{K}\left[\tilde{W}_{j}^{1} + \tilde{W}_{j}^{r} + \ldots + \tilde{X}_{j}^{K}\right] \tag{10}$$

being: $\tilde{X}_{ij}^{r}$: scores of the alternative A_i with respect to the criterion C_j given by the decision-maker D_r; $\tilde{W}_{ij}$: weight of criterion given by each decision maker.

Step 2: Building Fuzzy $\tilde{D}$ decision matrix for the scores of the alternatives and a Fuzzy vector W for the criteria weight according to the Equation 11 (Lima & Carpinetti, 2015).

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_j \\ A_n \end{array}\!\!\begin{array}{c} \begin{array}{ccc} C_1 & C_j & C_m \end{array} \\ \begin{bmatrix} \tilde{X}_{11} & \tilde{X}_{1j} & \tilde{X}_{1m} \\ \vdots & \vdots & \vdots \\ \tilde{X}_{n1} & \tilde{X}_{nj} & \tilde{X}_{nm} \end{bmatrix} \end{array} \tag{11}$$

Step 3: Normalization of matrix $\tilde{D}$ through a linear transformation scale. The normalized matrix $\tilde{R}$ is given by the Equations 12 to 14 (Lima et al., 2014):

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m X n} \tag{12}$$

$$\tilde{r}_{ij} = \left(\frac{l_{ij}}{u_j^{+}}, \frac{m_{ij}}{u_j^{+}}, \frac{u_{ij}}{u_j^{+}}\right), u_j^{+} = \max_i u_{ij}\left(\text{benefits criteria}\right) \tag{13}$$

$$\tilde{r}_{ij} = \left(\frac{l_j^{-}}{u_{ij}}, \frac{l_j^{-}}{m_{ij}}, \frac{l_j^{-}}{l_{ij}}\right), l_j^{-} = \min_i l_{ij}\left(\text{costs criteria}\right) \tag{14}$$

Step 4: Weighting the matrix D by multiplying the weights w_j by the elements r_{ij} of the normalized matrix according to Equations 15 and 16 (Lima & Carpinetti, 2015):

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\,X\,n} \tag{15}$$

$$\tilde{v}_{ij} = \tilde{r}_{ij} * \tilde{W}_j \tag{16}$$

Step 5: Definition of the Fuzzy Positive Ideal Solution (FPIS, A^+) and Fuzzy Negative Ideal Solution (FNIS, A^-), where $v_j^+ = (1,1,1)$ and $v_j^- = (0,0,0)$, by Equation 17 and 18 (Lima et al., 2014; Lima & Carpinetti, 2015):

$$A^+ = \left\{\tilde{V}_1^+, \tilde{V}_j^+, \ldots, \tilde{V}_m^+\right\} \tag{17}$$

$$A^- = \left\{\tilde{V}_1^-, \tilde{V}_j^-, \ldots, \tilde{V}_m^-\right\} \tag{18}$$

Step 6: Calculate the distances D_i^+ between the values of FPIS and the scores of the alternatives of the R matrix. Similarly, calculate the distances D_i^- between the FNIS values and the scores of the alternatives through the Equations 19 to 21 (Lima et al., 2014; Lima & Carpinetti, 2015):

$$D_i^+ = \sum_{j=1}^{n} d_V\left(\tilde{V}_{ij}, \tilde{V}_j^+\right) \tag{19}$$

$$D_i^- = \sum_{j=1}^{n} d_V\left(\tilde{V}_{ij}, \tilde{V}_j^-\right) \tag{20}$$

$$d(\tilde{x}, \tilde{z}) = \sqrt{\frac{1}{3}\left[(l_x - l_z)^2 + (m_x - m_z)^2 + (u_x - u_z)^2\right]} \tag{21}$$

Step 7: Calculate the approximation coefficient CC_i through Equation 22 and elaborate the alternatives ranking. The ranking is formed from the decreasing ordering of the CC_i values. The closer to 1, the better is the overall performance of the alternative (Uysal & Tosun, 2012).

$$CC_i = \frac{D_i^-}{\left(D_i^+ + D_i^-\right)} \tag{22}$$

Lima & Carpinetti (2015) and Lima et al. (2014) performed comparisons between Fuzzy TOPSIS and other techniques, presenting the benefits of each one. Regarding group decision-making, other techniques for aggregating decision makers′ opinions can be used, since they can better represent the problem under investigation (Chen, 2000).

4 Proposed decision model of supplier evaluation and selection for industrial maintenance

The proposed decision model is based on Lima & Carpinetti (2016), being divided into four stages. The steps to create the model are the following:

- Step 1: Seeks to identify and define the main criteria for industrial maintenance problem that will be analyzed by decision makers;
- Step 2: Seeks to aggregate the most recent criteria into two dimensions for the application of the proposed categorization;
- Step 3: Consists of an application of Fuzzy TOPSIS to evaluate the criteria of each dimension of the matrix;
- Step 4: Finally in step 4, the results obtained in stage three are evaluated, and the suppliers are inserted in the categorization matrix.

The main criteria to be analyzed for supplier evaluation and selection were identified. Criteria that will be considered in the proposed model, and that are also detailed in the research of Picanto et al. (2014) are listed in Table 1.

According to topic 3 and based on the criteria selected for evaluation, cost and reliability were defined as the two dimensions of the categorization matrix. In this way, each group of criteria is evaluated individually by its respective Fuzzy TOPSIS model. Figure 1 presents the framework with the dimensions of the categorization matrix and the sets of criteria that are evaluated individually.

The application of this decision-making model should involve the participation of one or more decision makers from different functional areas involved in the supplier evaluation and selection process (Lima & Carpinetti, 2016). Decision makers should quantify the level of importance of all criteria by considering the competitive strategy adopted by the company (Tsang, 2002). According to the resulting categorization of each potential supplier, action plans can be developed to select, manage and provide feedback to suppliers (Osiro et al., 2014). Next, different suppliers groups considered in the model are detailed.

Group I: suppliers in this group are considered inadequate and must be replaced by suppliers. In this case, the performance evaluation presents a supplier with high maintenance costs and low reliability, which are inversely desirable;

Group II: suppliers allocated to this group are classified as high reliability and high maintenance cost. These suppliers can be selected as long as there are efforts to reduce maintenance costs;

Group III: suppliers in this group are classified as low reliability and low maintenance cost. Thus, suppliers can be selected as long as there are efforts in increasing reliability. The reliability dimension is directly linked to the quality of the maintenance service;

Group IV: Suppliers allocated to this group are classified as strategic because of their high

Table 1. Criteria selected and considered in the model.

Selected criteria	Description
Preventive maintenance cost (C1)	Sum of the total and direct costs with preventive maintenance in a given period. Maintenance values performed periodically.
Corrective maintenance cost (C2)	Sum of the total and direct costs with corrective maintenance in a given period. Maintenance values performed on an emergency and non-scheduled basis.
Predictive maintenance cost (C3)	Sum of the total and direct costs with predictive maintenance in a given period. Inspection values of monitored parameters and performed maintenance if necessary.
Opportunity cost for production loss (C4)	Represents implicit costs and seeks to analyze what is proposed, allowing to act on results. Cost of non-produced units due to unplanned outages.
Management cost (C5)	It represents the administrative costs. It can represent direct costs related to maintenance management and also implicit costs such as those related to flexibility and relationship.
OEE- *Overall Equipment Effectiveness* (C6)	It takes into account performance, availability, and equipment quality.
MTTF- *Mean Time to Failure* (C7)	Estimated time for the interval between failures of a no repairable component.
MTBF – *Mean Time Between Failures* (C8)	Estimated time for the interval between failures of a repairable component.
MTTR- *Mean Time To Repair* (C9)	Represents the average time elapsed for the equipment repair.
Conformity (C10)	Represents if whether was requested has been accomplished.
Number of processes /improvements (C11)	Criteria for evaluating the identification of opportunities for improvement and development of processes and procedures.
Safety (C12)	Safety offered to employees and the environment, seeking satisfaction in the workplace.

Source: Adapted from Picanto et al. (2014).

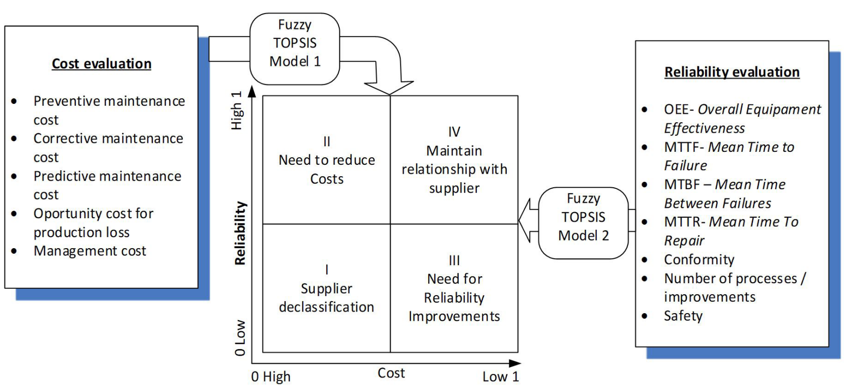

Figure 1. Research Framework for supplier evaluation. Source: Elaborated by the authors (2016).

performance. In this way, suppliers evaluated have a low maintenance cost and a high level of reliability, providing greater competitive advantages. Suppliers in this quadrant must be selected.

5 Pilot application

A pilot application of the model was carried out in a sugar-energy company. The analyzed problem addresses the evaluation and selection of the best alternative of industrial maintenance of agricultural machines responsible for raw material collection. This production sector is directly dependent on the sector that supplies raw material used in the production process. In this way, it is necessary to have a balance in order to prevent interruptions of raw materials supply. However, the excess of raw material can cause productivity losses due to the degradation of the organic material. Thus, it is essential that there is an efficient system of machines maintenance to efficiently meet the production sector, avoiding both the lack of raw material and the overproduction (high stock) aiming to assure the right level of service.

In the case analyzed, only two possibilities of maintenance services were identified. The first maintenance alternative refers to the maintenance itself, which is a current practice of the company. The second alternative is the outsourcing of maintenance to a single supplier capable of servicing the company. Three decision makers (TD) directly linked to maintenance participated in the application of the proposed model. Those responsible for the suppliers' evaluation were respectively: fleet control coordinator (TD 1), agricultural operations analyst (TD 2) and agricultural manager (TD 3). The interviewees were chosen according to the proximity and familiarity regarding the maintenance activities, and the initial contact with the specialists occurred by telephone. Each decision maker evaluated the performance of the maintenance alternatives for each criterion individually. In order to facilitate the evaluation, linguistic terms were assigned for the evaluation of supplier performance and for assigning the weight of the criteria (described in Table 2), which were later translated into triangular Fuzzy numbers as shown in Figure 2.

Initially, each decision maker assigned linguistic values to evaluate the alternatives performance of each dimension and their respective weights. Tables 3-8 present the results of the individual evaluations, which are the input data for the technique application.

From the individual decision makers' evaluations, Fuzzy numbers of the individual evaluations are aggregated using Equations 9 and 10 and normalized according to Equations 12-14. Tables 9 and 10 show the weighting of the normalized values according to the criteria weights as shown on Equations 15 and 16.

Tables 11-14 show the result of the calculations from the distances D_i^+ and D_i^- between the FPIS and FNIS values and the scores of the matrix alternatives using Equations 19-21.

Finally, Tables 15 and 16 present the result of calculations of approximation coefficient and the ranking of each alternative. To obtain the coefficient, Equation 22 was used.

According to the results obtained in the pilot study, Alternative 1 regarding the maintenance made by the company itself would be allocated in the quadrant III of the categorization matrix, presenting the best performance in costs and the worst performance in reliability. However, the option of outsourcing (Alternative 2) would be allocated in the quadrant II of the categorization matrix, due to its better performance in the reliability dimension and worse result in the cost dimension. Thus, none of the evaluated alternatives proved a strategic supplier; also, any choice of suppliers of maintenance services may present the necessity of improvements in the poor dimension.

Although alternative 1 presents a better overall performance, the final choice of the supplier will depend on the strategies adopted by the buying organization, as well as the difficulties of each alternative (Krause et al., 1998). If the company has a high degree of tacit information and the reliability improvement is viable, vertical integration will be an alternative with great potential (Dyer & Nobeoka, 2000). On the other hand, if the company focus on its core competencies, the outsourcing option should be favored (Dyer et al., 1998).

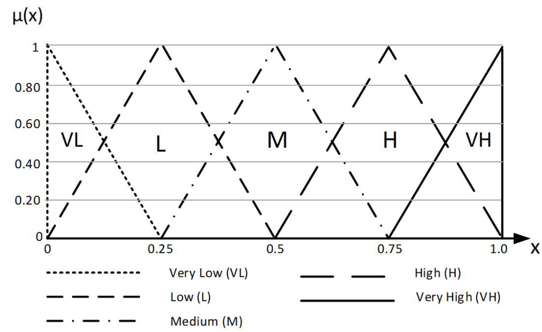

Figure 2. Triangular Fuzzy Numbers for criteria weights and performance evaluation. Source: Elaborated by the authors (2016).

Table 2. Linguistic terms and Fuzzy numbers for weights and criteria performance.

Linguistic terms	Triangular Fuzzy Number		
	l	m	u
Very Low (VL)	0.00	0.00	0.25
Low (L)	0.00	0.25	0.50
Medium (M)	0.25	0.50	0.75
High (H)	0.50	0.75	1.00
Very High (VH)	0.75	1.00	1.00

Source: Elaborated by the authors (2016).

Table 3. Linguistic evaluation of the decision maker 1 (DM 1) for the cost dimension.

DM 1	C1	C2	C3	C4	C5
Alternative 1	VH	VH	M	VH	H
Alternative 2	L	L	VH	L	L
Weight vector	VH	VH	H	H	H

Source: Elaborated by the authors (2016).

Table 4. Linguistic evaluation of the decision maker 2 (DM 2) for the cost dimension.

DM 2	C1	C2	C3	C4	C5
Alternative 1	M	L	M	H	H
Alternative 2	L	VL	L	H	H
Weight vector	VH	VH	VH	M	M

Source: Elaborated by the authors (2016).

Table 5. Linguistic evaluation of the decision maker 3 (DM 3) for the cost dimension.

DM 3	C1	C2	C3	C4	C5
Alternative 1	M	L	M	L	M
Alternative 2	M	M	M	M	M
Weight vector	VH	VH	VH	M	M

Source: Elaborated by the authors (2016).

Table 6. Linguistic evaluation of the decision maker 1 (DM 1) for the reliability dimension.

DM 1	C6	C7	C8	C9	C10	C11	C12
Alternative 1	M	VL	M	M	VH	VH	VH
Alternative 2	L	VH	L	L	L	L	L
Weight vector	H	M	M	M	VH	VH	VH

Source: Elaborated by the authors (2016).

Table 7. Linguistic evaluation of the decision maker 2 (DM 2) for the reliability dimension.

DM 2	C6	C7	C8	C9	C10	C11	C12
Alternative 1	M	L	M	M	H	M	M
Alternative 2	H	L	H	M	VH	VH	H
Weight vector	M	L	L	M	VH	M	VH

Source: Elaborated by the authors (2016).

Table 8. Linguistic evaluation of the decision maker 3 (DM 3) for the reliability dimension.

DM 3	C6	C7	C8	C9	C10	C11	C12
Alternative 1	L	L	L	L	M	M	M
Alternative 2	M	M	L	M	H	H	H
Weight vector	M	L	L	M	VH	VH	VH

Source: Elaborated by the authors (2016).

Table 9. Normalized and weighted values according to the weight of each criterion belonging to costs dimension.

Normalized and weighted values	C1			C2			C3			C4			C5		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
Alternative 1	0.50	0.80	1.00	0,38	0.75	1.00	0.33	0.67	1.00	0.50	0.80	1.00	0.45	0.73	1.00
Alternative 2	0.20	0.40	0.70	0.13	0,38	0.75	0.44	0.78	1.00	0.30	0.60	0.90	0.27	0.55	0.82
Weights	0.75	1.00	1.00	0.75	1,00	1.00	0.67	0.92	1.00	0.33	0.58	0.83	0.33	0.58	0.83

Source: Elaborated by the authors (2016).

Table 10. Normalized and weighted values according to the weight of each criterion belonging to reliability dimension.

Normalized and weighted values	C6			C7			C8			C9			C10			C11			C12		
	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u	l	m	u
Alternative 1	0.07	0.32	0.74	0.00	0.07	0.32	0.02	0.21	0.58	0.06	0.31	0.75	0.41	1.00	1.00	0.29	0.67	0.92	0.38	0.80	1.00
Alternative 2	0.11	0.39	0.83	0.04	0.26	0.58	0.02	0.21	0.58	0.06	0.31	0.75	0.34	0.73	0.91	0.29	0.67	0.92	0.30	0.70	1.00
Weights	0.33	0.58	0.83	0.08	0.33	0.58	0.08	0.33	0.58	0.25	0.50	0.75	0.75	1.00	1.00	0.58	0.83	0.92	0.75	1.00	1.00

Source: Elaborated by the authors (2016).

Table 11. Result of distance calculations between the alternatives and the ideal positive solution for the cost dimension.

D_i^+	C1	C2	C3	C4	C5	Sum
Alternative 1	0.38	0.44	0.50	0.58	0.60	2.50
Alternative 2	0.63	0.65	0.44	0.66	0.68	3.05

Source: Elaborated by the authors (2016).

Table 12. Result of distance calculations between the alternatives and the ideal negative solution for the cost dimension.

D_i^-	C1	C2	C3	C4	C5	Sum
Alternative 1	0.77	0.74	0.69	0.56	0.55	3.31
Alternative 2	0.47	0.49	0.73	0.48	0.44	2.61

Source: Elaborated by the authors (2016).

Table 13. Result of the distance calculations between the alternatives and the ideal positive solution for the reliability dimension.

D_i^+	C6	C7	C8	C9	C10	C11	C12	Sum
Alternative 1	0.57	0.79	0.67	0.58	0.20	0.45	0.38	3.64
Alternative 2	0.52	0.64	0.67	0.58	0.29	0.45	0.44	3.59

Source: Elaborated by the authors (2016).

Table 14. Result of the distance calculations between the alternatives and the ideal negative solution for the reliability dimension.

D_i^-	C6	C7	C8	C9	C10	C11	C12	Sum
Alternative 1	0.47	0.19	0.36	0.47	0.85	0.68	0.77	3.79
Alternative 2	0.53	0.37	0.36	0.47	0.70	0.68	0.73	3.83

Source: Elaborated by the authors (2016).

Table 15. Results of each alternative and cost dimension ranking.

	Approximation Coefficient	Ranking
Alternative 1	0.57	1
Alternative 2	0.46	2

Source: Elaborated by the authors (2016).

Table 16. Results of each alternative and reliability dimension ranking.

	Approximation Coefficient	Ranking
Alternative 1	0.49	2
Alternative 2	0.50	1

Source: Elaborated by the authors (2016).

6 Conclusion

This paper presents a proposal of a supplier evaluation model for industrial maintenance using Fuzzy TOPSIS. Cost and reliability were presented as the main criteria analyzed in decision-making for supplier selection of industrial maintenance. These criteria were transformed into dimensions of a categorization matrix, being subdivided into other criteria that sought to portray the clients' needs.

Fuzzy TOPSIS provided to decision makers an easy expression of the individual opinions about the maintenance alternatives and the weights of the analyzed criteria, due to the use of linguistic terms that were later transformed into Fuzzy numbers. The proposed categorization matrix facilitated the suppliers analysis, as well as the strategic direction of the company (concerning the decision to carry out the own maintenance or to outsource it), and to promote feedback to suppliers.

The application of the model in a sugarcane industry enabled the illustration of the proposed model, presenting two options of maintenance services that were allocated in two categories within the research framework: quadrant II and quadrant III. The present research does not intend to generalize results, but rather to propose a model that can be used in several situations of evaluation and selection of industrial maintenance suppliers. A future research opportunity is the inclusion of a wide range of suppliers to be evaluated from the proposed model. It was possible to observe divergences between the analyses of the decision makers that can present tendentious opinions and influence the results negatively. Another opportunity for future research is the use of methods of opinions´ aggregation, contributing to group decision making topic. Finally, other multi-criteria techniques can be used and the results from these techniques could be compared.

Acknowledgements

To CAPES (001) and FAPESP (2016/18807-6; 2016/14618-4) for financial support.

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