

Evaluating supplier sustainability using fuzzy 2-tuple representation

Avaliação da sustentabilidade de fornecedores utilizando a representação linguística fuzzy 2-tuple

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Abstract: In the last years, the participation of suppliers in the development, production, and distribution of products has increased. In this way, the sustainability of an organization depends more and more on these partners. The supplier sustainability assessment must be based on the economic, environmental and social tripod called the triple bottom line (TBL). Due to the recent adoption of qualitative metrics related to environmental and social issues in business management, models that deal with qualitative assessments based on experts' judgments have been required. This paper proposes a supplier sustainability assessment model based on fuzzy 2-tuple linguistic representation using TBL criteria. A pilot application involving the evaluation of 11 suppliers using 13 criteria was carried out in a company that manufactures agricultural products. The application results indicate that supplier 8 presents the higher performance. The criteria evaluated as the most relevant are delivery schedule and product quality. Due to the use of fuzzy 2-tuple representation, the proposed model presents some advantages over the previous similar models, such as the ability to model quantitative and qualitative criteria as well as categorize the supplier's overall performance into groups defined by fuzzy linguistic terms.

Keywords: Supplier sustainability assessment; Fuzzy 2-tuple; Triple bottom line; Multicriteria decision making.

Resumo: Nos últimos anos, a participação de fornecedores no desenvolvimento, produção e distribuição de produtos aumentou. Dessa forma, a sustentabilidade de uma organização depende cada vez mais desses parceiros. A avaliação da sustentabilidade dos fornecedores deve basear-se no tripé econômico, ambiental e social, denominado *triple bottom line* (TBL). Devido à recente adoção de métricas qualitativas relacionadas a questões ambientais e sociais na gestão de negócios, modelos que lidam com avaliações qualitativas baseadas em julgamentos de especialistas tornaram-se relevantes. Este artigo propõe um modelo de avaliação da sustentabilidade de fornecedores baseado na representação linguística *fuzzy 2-Tuple*, usando os critérios do TBL. Uma aplicação piloto envolvendo a avaliação de 11 fornecedores usando 13

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cr terios foi realizada em uma empresa que fabrica produtos agr colas. Os resultados da aplica o indicam que o fornecedor 8 apresenta o melhor desempenho. Os cr terios avaliados como os mais relevantes s o programa o de entrega e qualidade do produto. Devido ao uso da representa o fuzzy 2-tuple, o modelo proposto apresenta algumas vantagens em rela o aos modelos anteriores, como a capacidade de modelar cr terios quantitativos e qualitativos, bem como categorizar o desempenho geral do fornecedor em grupos definidos pelos termos lingu sticos.

Palavras-chave: Avalia o da sustentabilidade de fornecedores; *Fuzzy 2-tuple*; *Triple bottom line*; Decis o multicrit rio.

1 Introduction

Supplier performance evaluation, as well as supplier selection, has been extensively studied in the literature (Ho et al., 2010; Zimmer et al., 2015). These problems have been predominantly addressed in the academic literature as a problem of multicriteria decision making (MCDM) in which several decision criteria are used for the assessment of possible suppliers (Chai et al, 2013). In this way, managers should define the most important criteria, evaluate the suppliers considering these criteria, and thus select or award the best-evaluated suppliers.

Nowadays companies have been looking for suppliers with sustainable practices in response to increasing demands for environmental and social requirements (Pagell et al., 2010). In addition, the sustainability of the supply chain is increasingly recognized as a way to achieve cost reduction and essential for the long-term profitability (Wang & Sarkis, 2013). Sustainable company is one that simultaneously generates economic, social and environmental benefits, known as Triple Bottom Line (TBL), contributing to sustainable development (Govindan et al., 2013). The economic benefits refer to the production, distribution, and consumption of products and services, in addition to the main measure of performance of most companies: profit. Social benefits deal with human capital, provision of fair wages, compliance with labor legislation, and provide an adequate working environment, with a focus on the health and safety of employees. Finally, environmental benefits are achieved when an organization manages the environmental impacts due to its economic activity (Ahi & Searcy, 2013).

The pursuit of economic, social, and environmental performance is increasingly recognized as an effective way to address some of the contemporary challenges of global supply chains (Wang & Sarkis, 2013). Since the social and environmental performance of a company can be affected by the social and environmental performance of its suppliers, new supplier performance evaluation criteria related to social and environmental responsibilities are now considered in addition to the traditional metrics such as cost, quality, delivery time and flexibility (Lee et al., 2009; B y k zkan &  if i, 2012).

In general, environmental and social criteria have a more subjective nature than economic criteria, presenting higher levels of vagueness and imprecision, consequently requiring a qualitative modelling approach, such as decision-making methods based on fuzzy set theory (Brandenburg et al., 2014). Several fuzzy approaches have been proposed to deal with managerial problems in the academic literature. Among these, fuzzy 2-tuple representation model has been widely used in solving MCDM problems under uncertainty, due to its simplicity and other characteristics as the capacity to aggregate qualitative and quantitative variables in a

continuous domain (Martínez & Herrera, 2012). Despite of this, we have not found models based on fuzzy 2-tuple for evaluating the sustainability of suppliers. Thus, this paper proposes a supplier sustainability assessment model based on fuzzy 2-tuple linguistic representation using TBL criteria. A pilot application involving assessment of 11 suppliers based on 13 criteria was carried out in an agricultural product manufacturer.

The paper is organized as follows: Section 2 reviews the literature about supplier sustainability evaluation. Section 3 reviews about fuzzy 2-tuple linguistic representation. Section 4 presents the proposed model. Section 5 shows an application in a real case and discuss the results. Section 6 presents the conclusions.

2 Supplier sustainability evaluation

According Seuring & Müller (2008), a sustainable supply chain can be defined as the “management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development”. In this sense, sustainable supply chain management is focused on maintaining economic, environmental, and social stability across the supply chain tiers for long-term sustainable growth (Dubey et al., 2017).

Supplier sustainability assessment is a critical activity for sustainable supply chain management. Zimmer et al. (2015, p. 3) state that it involves continuous monitoring of the supplier performance considering “[...] the compliance of specified minimum requirements and the performance improvement taking into account the three dimensions of sustainability”. Therefore, supplier sustainability assessment helps managers to identify suppliers who need attention or suppliers that should be replaced, as well as evaluate the progress or success of supplier development initiatives (Zimmer et al., 2015).

The evaluation of suppliers’ sustainability is not consolidated as the traditional performance evaluation of suppliers. Since the adoption initiatives of environmental and social criteria are recent, the companies have scarce standards and consolidated procedures for gathering and treating these kinds of data (Govindan et al., 2015). The difficulty of obtaining data related to environmental and social issues in companies has limited the amount of quantitative research on supply chain sustainability. Thus, the development of knowledge about supply chain sustainability requires more quantitative studies (Ansari & Kant, 2017).

The supplier evaluation process has been predominantly addressed in the academic literature as a multicriteria decision making problem (Chai et al., 2013; Zimmer et al., 2015). The main criteria used in these processes are: quality, delivery, price/cost, manufacturing capability and service (Ho et al., 2010). However, over the last few years, consumers have been more concerned with environmental and social issues, as industrial and commercial activities have caused negative impacts on the planet’s environmental and social conditions (Ahi & Searcy, 2015; Giannakis & Papadopoulos, 2016; Ansari & Kant, 2017). This has led companies to include sustainable evaluation criteria in their strategic plans.

Economic criteria are the most consolidated and those that have been most studied for supplier evaluation among the three dimensions of TBL. Since the seminal work of Dickson (1966), economic criteria like product quality, lead time and cost of product have been received great attention (Kannan & Tan, 2002). Recently, environmental criteria have received more attention, due to the increasing concern of society for

environmental issues and the establishment of governmental laws and regulations (Ahi & Searcy, 2013). Social criteria remain the least studied, although companies have increased their concern to meet the needs of all stakeholders (Brandenburg et al., 2014). Table 1 shows several economic, environment and social criteria according to literature. The function of this table is not to identify all the criteria reported in the literature, but it can be used as a checklist for choosing initial criteria in a supplier sustainability assessment process.

Table 1. Criteria of supplier sustainability assessment.

Economic		Environmental		Social	
Criterion	Author(s)	Criterion	Author(s)	Criterion	Author(s)
Cost of product	Kuo et al. (2010)	Green materials	Govindan et al. (2015)	Coordenation of social projects	Govindan et al. (2013)
Transaction costs	Kuo et al. (2010)	Remanufacture	Buyukozkan & Cifci (2011)	Child/forced labour risk	Feil et al. (2015)
Environmental costs	Ahi & Searcy (2015)	Recycle	Buyukozkan & Cifci (2011)	Training programs for employees	Feil et al. (2015)
Transportation cost	Kuo et al. (2010)	Carbon footprint	Govindan et al. (2015)	Relationship with stakeholders	Govindan et al. (2015)
Lead time	Govindan et al. (2013)	ISO 14001 certification	Chen et al. (2010)	Employee satisfaction	Feil et al. (2015)
Delivery schedule	Kuo & Lin (2012)	Green design of product	Chen et al. (2010)	Customers' satisfaction	Ahi & Searcy (2015)
Flexibility	Ahi & Searcy (2015)	Reduction of solid wastes	Ahi & Searcy (2015)	Stakeholder empowerment	Govindan et al. (2013)
Quality system	Kuo & Lin (2012)	Reduction of hazard materials	Buyukozkan & Cifci (2011)	Suspension due to accidents	Feil et al. (2015)
Product quality	Govindan et al. (2015)	Sustainable waste management	Govindan et al. (2015)	Frequent and honest communication	Govindan et al. (2015)
Management commitment of quality	Kuo et al. (2010)	Use sustainable packaging	Buyukozkan & Cifci (2011)	Supporting community projects	Feil et al. (2015)
Reject rate	Kuo et al. (2010)	Emission of greenhouse gases	Ahi & Searcy (2015)	Health and safety	Govindan et al. (2013)
Technology capability	Govindan et al. (2015)	Energy efficiency	Ahi & Searcy (2015)	Educational institutions	Govindan et al. (2013)
Research and development	Govindan et al. (2013)	Green purchasing	Chen et al. (2010)	Working conditions	Govindan et al. (2013)
Design capability	Kuo et al. (2010)	Environmental policies	Ahi & Searcy (2015)	Human resource management skill	Wu & Barnes (2010)
Payment policy	Govindan et al. (2015)	Pollution prevention	Ahi & Searcy (2015)	Government relationships	Wu & Barnes (2010)
Financial status	Kuo & Lin (2012)	Validity of clean technique	Govindan et al. (2015)	Reputation	Wu & Barnes (2010)
Return on investment	Ahi & Searcy (2015)	Water consumption	Ahi & Searcy (2015)	Corruption and Fraud	Rahdari & Anvary Rostamy (2015)
Profitability of supplier	Chen et al. (2010)	Reuse ratio	Subramanian & Gunasekaran (2015)	Employee volunteer hours	Searcy et al., (2016)
Financial issues	Govindan et al. (2015)	Renewable energy consumption	Feil et al. (2015)	Serious and fatal accidents	Feil et al. (2015)
After service	Ahi & Searcy (2015)	Non-renewable energy consumption	Feil et al. (2015)	Local community influence	Subramanian & Gunasekaran (2015)

Source: Proposed by Authors.

2.1 Decision models for supplier sustainability evaluation

The literature presents several quantitative models to support decision making problems related to sustainable supply chain management. Dai & Blackhurst (2012) propose a model to support weighting of sustainability criteria and selection of sustainable supplier based on the combination of the methods AHP (Analytic Hierarchy Process) and QFD (Quality Function Deployment). Tajbakhsh & Hassini (2015) proposed a data envelopment analysis approach to assess sustainability of supply chains. Osiro et al. (2018) proposed a model based on hesitant fuzzy and QFD to select supply chain sustainability metrics. Akman (2015) combined fuzzy c-means and VIKOR (VišeKriterijumska Optimizacija I Kompromisno Resenje) to deal with supplier performance evaluation in order to include green supplier development programs. Similarly, Awasthi & Kannan (2016) applied fuzzy NGT (Nominal Group Technique) and VIKOR to deal with selection of green supplier development program. Despite the wide variety of studies that presents decision models related to sustainable supply chain management, few studies focus on the evaluation of supplier sustainability.

In order to identify the previous studies that propose quantitative decision models for supplier sustainability assessment, a bibliographical research was done using the google scholar tool, as well as the databases IEEE-Xplore, Scopus, Emerald Insight, Taylor & Francis and Science Direct. We used the search string “supplier AND sustainability AND assessment”, “supplier AND sustainability AND evaluation”, “sustainable AND supplier AND assessment” and “sustainable AND supplier AND evaluation”. The selection of papers was made based on the analysis of the title, abstract and (in some cases) the body of the text of the first 100 studies displayed as a result in each database. From this analysis, we have found only 9 studies that propose quantitative decision models to support the supplier sustainability evaluation. Table 2 briefly describes the decision models proposed by these studies. It is important to note that due to the scope of the present study, this bibliographic survey does not include decision models that only support the selection of sustainable suppliers, which are more frequent in the literature.

Table 2. Decision making models for supplier sustainability assessment.

Proposed by	Scope	Decision technique(s)	Decision criteria
Baskaran et al. (2012)	Evaluation and categorization of suppliers' sustainability in Indian textile industry	Grey approach	Discrimination, abuse of human rights, child labor, long working hours, unfair competition, and pollution.
Govindan et al. (2013)	Measurement of sustainability performance of a supplier based on TBL approach	Fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	Cost, delivery, reliability, quality, technology capability, pollution production, resource consumption, eco-design, environmental management system, and employment practices, among others.
Bai and Sarkis (2014)	Definition and application of sustainable supplier performance indicators	Rough set theory and DEA (Data envelopment analysis)	Cost, time, quality, flexibility, and innovation.

Table 2. Continued...

Proposed by	Scope	Decision technique(s)	Decision criteria
Trapp and Sarkis (2016)	Selection and development of sustainable suppliers	Integer programming	Constraints related to risks, quality, delivery time, training budget, minimum capacity, among others.
Zhou et al. (2016)	Selection and evaluation of sustainable suppliers	DEA, fuzzy sets of type-2 and chance constrained programming	Technology capability, financial capability, environmental cost, and cost of work safety and labor health.
Luthra et al. (2017)	An integrated framework for sustainable supplier selection and evaluation in supply chains	AHP (Analytical Hierarchy Process) and VIKOR (ViseKriterijumska Optimizacija I Kompromisno Resenje)	Price of product, quality of product, flexibility, environment management systems, green design and purchasing, green management, waste management & pollution prevention, environmental competencies, occupational health & safety systems, the rights of stakeholders, among others.
Torres-Ruiz and Ravindran (2018)	A multiple criteria framework for the sustainability risk assessment of a supplier portfolio	AHP	Reputation, access to capital, supply security, regulation, efficiency and productivity.
Li et al. (2018)	Sustainability evaluation via variable precision rough set approach	Rough set theory and TODIM (an acronym in Portuguese of Interactive and Multicriteria Decision Making)	Quality, flexibility, financial performance, technology and innovation, pollution control, environmental management, resource use efficiency, influence on natural environment, employment, product stewardship, social governance.
Liu et al. (2019)	A fuzzy decision tool to evaluate the sustainable performance of suppliers	Fuzzy AHP and Fuzzy TOPSIS	Human toxicity, water depletion, climate change, land occupation, marine ecotoxicity, feed manufacturing cost, total feed system cost, waste, labor cost, work hours, localness, among others.

Source: Proposed by Authors.

As can be seen in Table 2, different multicriteria decision making techniques and mathematical programming methods have been tested in the sustainability assessment of suppliers, such as AHP (Luthra et al., 2017; Torres-Ruiz & Ravindran, 2018), Fuzzy AHP (Liu et al., 2019), VIKOR (Luthra et al., 2017), Fuzzy TOPSIS (Govindan et al., 2013; Liu et al., 2019), DEA (Bai & Sarkis, 2014; Zhou et al., 2016), TODIM (Li et al. 2018), among others. Some characteristics that distinguish these techniques are: ability to model quantitative and/or qualitative criteria; number of alternatives and criteria that can be adopted; type of output (ordering or categorization of alternatives);

support for group decision making; and ability to include and exclude alternatives without affect the consistency of results.

Since mathematical programming methods such as integer programming (Trapp & Sarkis, 2016) and DEA (Zhou et al., 2016) are able to model only quantitative criteria, most studies use some appropriate approach to deal with uncertainty due to the qualitative nature of some environmental and social criteria. These approaches include fuzzy set theory (Govindan et al., 2013; Zhou et al., 2016), grey approach (Baskaran et al., 2012) and rough set theory (Bai & Sarkis, 2014). However, none of these techniques is able to model both quantitative and qualitative sustainability criteria.

While most of the models showed in Table 2 support solely ordering of suppliers (Govindan et al., 2013; Bai & Sarkis, 2014; Trapp & Sarkis, 2016; Zhou et al., 2016; Luthra et al., 2017; Li et al., 2018; Torres-Ruiz & Ravindran, 2018), the models proposed by Baskaran et al. (2012) and Liu et al. (2019) allows categorization of supplier's overall performance into groups whose limits are defined by means of grey value range and crisp numbers, respectively. It is worth to note that in the reviewed literature were not found supplier sustainability assessment models that enable categorization of supplier's overall performance into groups defined by linguistic terms and quantified using fuzzy numbers.

In a study of systematic literature review, Zimmer et al. (2015) analyzed 143 papers that propose decision models for sustainable supplier selection and evaluation published. These authors have pointed out that most of 80 percent of models are focused on the supplier selection step. In addition, Zimmer et al. (2015) concluded that AHP and ANP are the most commonly applied methods. Govindan et al. (2015) reviewed 33 studies on decision models for green supplier selection and evaluation. Differently from Zimmer et al. (2015), they found that the most applied techniques are based on fuzzy set theory. However, none of the reviewed studies by Zimmer et al. (2015) and Govindan et al. (2015) have applied fuzzy 2-tuple linguistic representation for supplier sustainability assessment.

3 Fuzzy 2-Tuple linguistic representation Model

In classical theory, the membership of a given element to a set corresponds to the fact that such element belongs or not to this set, i.e. the domain is binary. A fuzzy set is a class of objects characterized by a membership function, which assigns a degree of inclusion of objects differently from classical theory. In this way, they can be partially included in more than one set simultaneously (Zadeh, 1973). This allows a better approximation of what happens in solving some real problems in which there are not only quantitative values but experts' evaluations with imprecision and vagueness. Due to these characteristics, fuzzy variables have been used to develop quantitative models addressed to aid the resolution of management problems like supplier selection and evaluation (Santos et al, 2017).

Fuzzy 2-tuple linguistic representation, proposed by Herrera & Martínez (2000a), has been adopted by researchers in different applications (Martínez & Herrera, 2012). In the 2-tuple model, a variable is represented by a pair of values (s_i, α) , where s_i is the i th linguistic term belonging to a predefined terms set S ; and α is defined as symbolic translation that expresses the distance from the original result of an aggregation operation β to centre of the closest membership function (s_i) in the linguistic term set S .

Lets $\beta \in [0, g]$ be the result of an aggregation operation of terms from the linguistic term set $S = \{s_0, \dots, s_g\}$, then the representation of β in 2-tuple can be obtained by (1).

$$\Delta(\beta) = (s_i, \alpha) \tag{1}$$

With

$$i = \text{round}(\beta) \tag{2}$$

$$\alpha = \beta - i, \tag{3}$$

The usual rounding operator is used in the expression $\text{round}(\beta)$, so if s_i is the nearest linguistic term of β , α is a value between $[-0.5, 0.5)$ representing the symbolic translation. Figure 1 shows how α represents the information gap between the result of aggregation operation β and the nearest predefined linguistic term s_i (Herrera & Martínez, 2000a).

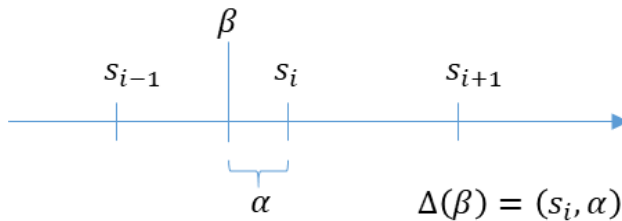


Figure 1. Representation of the difference between β and s_i . Source: Santos et al. (2017).

The β standard enables aggregation operations to be performed in a continuous domain. Thus, unlike solutions based on symbolic methods or extension principle, fuzzy 2-tuple can aggregate the linguistic terms without loss of information (Herrera & Martínez, 2000a). After aggregation operation, Equation 1 can be used to make β information into the original predefined linguistic labels.

The characteristics of the memberships degree of the linguistic terms are fundamental to allow operations with β format information and the aggregation of qualitative and quantitative criteria, without any loss of information. According to Herrera & Martínez (2000b), being $S = \{s_0, \dots, s_g\}$ a set of linguistic terms, these three characteristics are:

1. S is a fuzzy partition, i.e., with $X = [0, I]$, we have $\sum_{i=1}^g \mu_{s_i}(x) = I, \forall x \in X$.
2. The membership functions of all its terms are triangular, i.e., $s_i = (a_i, b_i, c_i)$.
3. The membership function of the characteristic value, b_i , is equal to 1. In other words, if $CV(s_i) = x$ then $\mu_{s_i}(x) = I$

Any quantitative criterion normalized to $\mathcal{G} \in [0, I]$ could be represented by fuzzy 2-tuple linguistic representation, without any loss of information, since $S = \{s_0, \dots, s_g\}$ satisfies these three conditions.

Different aggregation operators can be used with variables in fuzzy 2-tuple linguistic representation. The weighted average operator proposed by Herrera and Martínez (Herrera & Martínez, 2000a) is used in this paper due to its simplicity and possibility to deal with multiple criteria considering different weights. Let a set of 2-tuples

$y = \{(x_1, \alpha_1), \dots, (x_n, \alpha_n)\}$ and its continuous representation $\{\beta_1, \dots, \beta_n\}$. For a weighting vector $w = \{w_1, \dots, w_n\}$, where $0 \leq w_i \leq 1$ and $\sum w_i = 1$, the weighted average μ is determined by (4).

$$\mu = \Delta(\sum w_i \cdot \beta_i) \quad (4)$$

The fuzzy 2-tuple linguistic representation was used in this proposal to evaluate supplier sustainability due to its flexibility and simplicity. This approach uses linguistic variables to evaluate qualitative criteria and allows the aggregation between quantitative and qualitative criteria in a continuous domain without loss of information, unlike what occurs in other methods of computing with words, based on the symbolic methods (Herrera & Martínez, 2000a, b). In addition, its mathematical operations are simple and allow applications using spreadsheets, such as MS Excel, which was used in the case study of this work.

4 Proposed model for supplier sustainability evaluation

The proposed model for supplier sustainability evaluation is divided into 4 steps as shown in Figure 2. In the first step, a group of experts (or decision makers) from different functional areas related to supply management should choose a set of criteria based on the TBL to evaluate the suppliers' sustainability. This can be done by conducting brainstorming among decision makers. Historical performance data of suppliers should also be considered for the purpose of using information already available to the purchasing company. The criteria chosen should be aligned with the company's competitive strategy and its supply chain(s). For example, buyer companies inserted green supply chains should primarily choose environmental criteria. Table 1 may help in determining the most relevant criteria for the sustainability evaluation process. Although choosing a greater number of criteria leads to a more detailed evaluation of suppliers, this may also require more time, human and financial resources for data collection, processing, analysis and dissemination of data. Therefore, it is important to select a balanced quantity of criteria.

In step 2, the 2-tuple representation is used to weight the criteria previously selected according to the company's purchasing strategy. In this paper, based on Herrera & Martínez (2000b), a linguistic term set with seven terms $S = \{s_0: \text{Nothing}, s_1: \text{Very Low}, s_2: \text{Low}, s_3: \text{Medium}, s_4: \text{High}, s_5: \text{Very High}, s_6: \text{Perfect}\}$ is adopted. Figure 3 shows the membership function of all the seven terms of S in the continuous domain of β . This linguistic term set satisfies the three conditions described in section 3, which make it possible to use Equation 1 without loss of information and represent quantitative criteria, if necessary. In this way, the experts use these linguistic terms to determine the weight of each criterion. Equation 4 could be used to aggregate the judgments of the decision makers and calculate the value of β for each criterion. Subsequently, these values are normalized to satisfy the conditions $0 \leq w_i \leq 1$ and $\sum w_i = 1$. Alternatively, the fuzzy QFD approaches suggested by Lima & Carpinetti (2016) and Osiro et al. (2018) can be adopted to select and weigh the criteria from a set of requirements. In these approaches, the selection of criteria also taking into account the difficulty of data collection to measure the supplier performance. On the other hand, the use of fuzzy 2-tuple linguistic representation requires less effort to collect and process data in order to obtain the weights of the evaluation criteria.

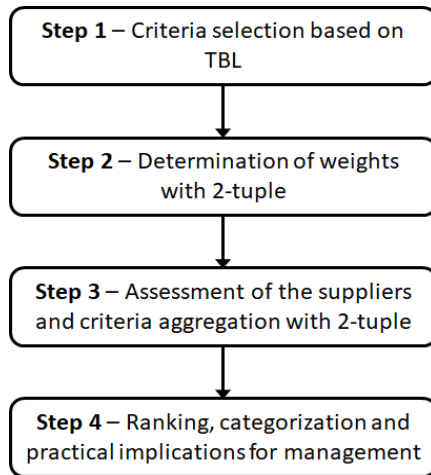


Figure 2. Framework of the proposed model. Source: Proposed by Authors. **Note:** TBL (Triple Bottom Line).

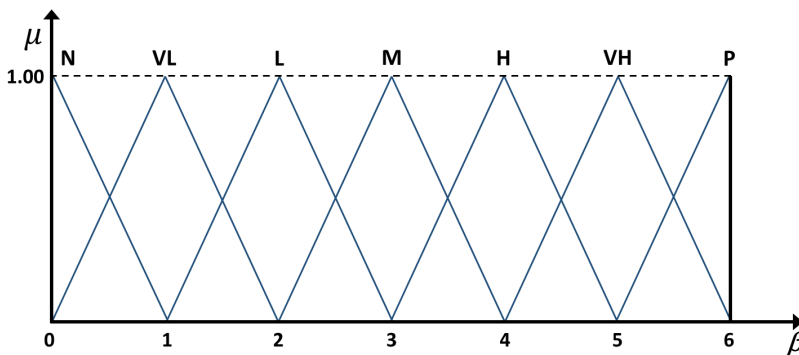


Figure 3. Membership functions of the terms in the continuous domain of β . Source: Herrera & Martínez (2000b). **Note:** N: Nothing, VL: Very Low, L: Low, M: Medium, H: High, VH: Very High, P: Perfect.

In step 3, using the linguistic term set S , experts should assess the score of the suppliers regarding each criterion. The suppliers scores should be based on the experience and intuition of decision-makers, as well as historical performance data available on internal documents and data base. External information sources also may be consulted, such as financial consultants and other customers of the evaluated suppliers. After defining the suppliers' score and the weight of the criteria, Equation 4 should be used to calculate of the supplier overall performance by aggregating the supplier scores on each criterion considering their relative weights.

Once aggregation results have been concluded, step 4 consists of ranking suppliers and categorizing into groups in order to highlight the best-performing suppliers, which can serve as a reference to others. Likewise, worst performing vendors should be scrutinized for possible development and improvement plans. Depending on the criteria in which each supplier performs less than expected, development programs may involve solving problems of process quality, cost reduction programs, waste reduction, capital and equipment supply, technical support, standardization of parts, certification

of suppliers, environmental programs, improvement of packaging, improvement of communication, among others.

The value of β that determine the ranking must be transformed into linguistic terms from Figure 3 to categorize the suppliers. In others words, these terms are the different categories of suppliers. Equations 2 and 3 transform a value of β into (S_i, α) format. For example, for a value of $\beta = 4.6$, Equation 2 determines $i = 5$ and Equation 3 determines $\alpha = -0.4$. As a result, we have $(VH, -0.4)$ and the category is "very high".

5 Application case

In order to illustrate the proposed model, a pilot application was carried out in an agricultural product manufacturer. The group of experts was composed by three managers, who sought consensus on the judgments related to the weighting of criteria and scores of the suppliers. Thus, there was no need to aggregate different judgments of the three managers. If the group had difficulties in achieving consensus, the different expert evaluations could be aggregated through Equation 4. Alternatively, techniques like Delphi could be used in the systematized search of the consensus.

During the application of the model, one of the authors of this proposal was available to guide the experts. For example, in the step 1, this author presented Table 1 for the experts' group with the purpose of assisting the discussions to select the TBL criteria. Table 3 presents the 13 criteria selected, which include 8 economic criteria, 2 environmental criteria and 3 social criteria. The chosen criteria indicate a greater concern of the managers with the economic dimension than with the environmental and social dimensions.

Table 3. Selected criteria for supplier assessment.

Dimension	Criterion	Id.
Economic	Cost of product	EC1
	Transportation cost	EC2
	Lead time	EC3
	Delivery schedule	EC4
	Product quality	EC5
	Research and development	EC6
	Payment policy	EC7
	After service	EC8
Environmental	ISO 14001 certification (Associação Brasileira de Normas Técnicas, 2015)	EN1
	Environmental policies	EN2
Social	Child/forced labour risk	S1
	Frequent and honest communication	S2
	Health and safety	S3

Source: Proposed by Authors.

In step 2, the experts judged the weights of the 13 criteria. The weighting of the criteria is determined by the choice of linguistic terms that are associated with integer values of β , as shown in Figure 3. Table 4 shows the evaluation of each criterion by means of the linguistic term in its second column and the respective value of β in the

third column. Thereafter, these β values were normalized to satisfy the conditions $0 \leq w_i \leq 1$ and $\sum w_i = 1$, determining the criteria weights as displayed in the last column.

In step 3, a set of 11 suppliers were analyzed. Table 5 shows the characterization of these suppliers in relation to their supplied material. The experts evaluated the performance of these suppliers using the linguistic terms of the set S as shown in Table 6. In order to aggregate the experts' judgments on supplier performance in each criterion, we use Equation 3 to convert the linguistic terms into β format and Equation 4 to determine the result of the aggregation. For example for supplier 1, we have: $\beta_1 = 0.109 \cdot 4 + 0.087 \cdot 3 + 0.109 \cdot 3 + \dots + 0.065 \cdot 5 + 0.087 \cdot 4 + 0.065 \cdot 5 = 3.91$. The last line of Table 6 presents all β results of the operations.

Table 4. Weights of the criteria.

Criterion	Assessment	\hat{a}	Weight
EC1	VH	5	0.109
EC2	H	4	0.087
EC3	VH	5	0.109
EC4	P	6	0.130
EC5	P	6	0.130
EC6	L	2	0.043
EC7	L	2	0.043
EC8	H	4	0.087
EN1	VL	1	0.022
EN2	VL	1	0.022
S1	M	3	0.065
S2	H	4	0.087
S3	M	3	0.065

Source: Proposed by Authors.

Table 5. Evaluated suppliers and their materials provided.

Supplier	Material provided
Sup1	Urea
Sup2	Ammonium nitrate 33%N
Sup3	Containers and covers
Sup4	Liquid Calcium Carbonate
Sup5	Urea
Sup6	Fertilizer 33%N
Sup7	Ammonium nitrate 33%N
Sup8	Zinc oxide
Sup9	Cobalt sulfate 20%CO
Sup10	Manganese carbonate
Sup11	Manganese ore - Manganese dioxide

Source: Proposed by Authors.

Finally in the last step, the list of suppliers is ranked in descending order according to their values of overall performance (β). Table 7 shows the supplier ranking with the β values and results of the categorization into groups. Table 7 shows the suppliers with the best performance in sustainability according to the selected TBL criteria. In addition, it warns about suppliers who pose risks to a sustainable supply.

Table 6. Supplier's assessment based on linguistic terms.

Criterion	Weight	Suppliers										
		Sup1	Sup2	Sup3	Sup4	Sup5	Sup6	Sup7	Sup8	Sup9	Sup10	Sup11
EC1	0.109	H	VH	VH	H	VH	M	VH	VH	H	H	VH
EC2	0.087	M	H	VH	M	H	H	H	VH	VH	H	L
EC3	0.109	M	H	P	M	VH	H	H	VH	VH	VH	M
EC4	0.130	M	VH	H	M	VH	H	VH	VH	H	H	M
EC5	0.130	P	L	VH	VH	H	H	M	P	H	VH	VH
EC6	0.043	M	L	VH	VH	L	VH	M	H	M	P	VL
EC7	0.043	VH	M	H	H	VH	H	H	H	H	VH	VH
EC8	0.087	L	M	VH	VH	M	H	M	VH	VH	VH	M
EN1	0.022	VH	L	M	VH	L	VH	VH	VH	VH	H	L
EN2	0.022	H	H	H	VH	L	H	VH	P	H	H	L
S1	0.065	VH	VH	H	VH	H	VH	VH	VH	H	VH	L
S2	0.087	H	M	VH	H	VH	VH	VH	VH	VH	VH	VH
S3	0.065	VH	H	M	VH	M	VH	VH	P	H	VH	L
Aggregation (\hat{a})		3.91	3.69	4.67	4.10	4.15	4.17	4.24	5.13	4.35	4.67	3.39

Source: Proposed by Authors.

Table 7. Ranking of suppliers.

Ranking	Supplier	\hat{a}	(s_i, \hat{a})	Group
1 st	Sup8	5.13	(VH, 0.13)	Very high
2 nd	Sup3	4.67	(VH, -0.33)	Very high
3 rd	Sup10	4.67	(VH, -0.33)	Very high
4 th	Sup9	4.35	(H, 0.35)	High
5 th	Sup7	4.24	(H, 0.24)	High
6 th	Sup6	4.17	(H, 0.17)	High
7 th	Sup5	4.15	(H, 0.15)	High
8 th	Sup4	4.10	(H, 0.10)	High
9 th	Sup1	3.91	(H, -0.09)	High
10 th	Sup2	3.69	(H, -0.31)	High
11 th	Sup11	3.39	(M, 0.39)	Medium

Source: Proposed by Authors

6 Results and discussions

The proposed model enables a performance analysis of the sustainability of the suppliers in supply chains, improving its decision-making process on development of partnerships, with the wide involvement of different departments. Through supplier evaluation records, various actors involved in the procurement process can share the same information in order to ensure consistent actions in supplier performance management.

As shown in Table 7, the performance of the suppliers 8, 3 and 10 stood out positively since their aggregate result was "very high". In this way, mainly supplier 8

can serve as reference as a sustainable supplier. On the other hand, supplier 11 presented the worst performance, with the aggregate result “medium”. An analysis of its worst evaluations shows that “very low” performance was achieved in the criterion EC6 (Research and development) and a “low” performance in EC2 (Transportation cost), EN1 (ISO 14001 certification), EN2 (Environmental policies), S1 (Child/forced labor risk) and S3 (Health and safety). A development action for this supplier in order to increase its sustainability should be focused on improving these factors, mainly EC2 because it is the criterion of greater weight.

The results suggest that the purchasing company was more concerned with its economic sustainability since among the 13 selected criteria, a total of 8 were from this dimension of the TBL. Environmental sustainability was the least critical since only 2 criteria from this dimension were selected; moreover, their weights were the smallest. Finally, social sustainability has received an intermediate importance between economic and environmental, since it had 3 selected criteria whose assigned weights were median values.

When comparing with previous studies, in relation to the weights of the criteria, application results are similar to ones found by Luthra et al. (2017), since economic criteria such as quality and cost have also been evaluated as the most relevant. On the other hand, it differs from Baskaran et al. (2012) and Govindan et al. (2015), in which environmental metrics such as pollution were given more importance.

Due to the use of fuzzy 2-tuple representation, the proposed model presents some advantages over the previous similar models. When compared to AHP and fuzzy-AHP methods, the proposed approach requires a smaller number of judgments from decision-makers. Another advantage is not requiring the application of tests to verify the consistency of comparative matrices, which contributes to make the decision making more agile. Unlike the models based fuzzy-AHP (Liu et al., 2019), the proposed model does not generate null weights for the criteria, nor does it limit the number of criteria that can be adopted. In addition, unlike AHP-based models (Torres-Ruiz & Ravindran, 2018), it does not generate ranking inversion nor does limit the number of suppliers that can be simultaneously assessed.

Other benefits over the previous models based on VIKOR (Luthra et al., 2017), Fuzzy TOPSIS (Govindan et al., 2013; Liu et al., 2019), DEA (Bai & Sarkis, 2014; Zhou et al., 2016), TODIM (Li et al. 2018), integer programming (Trapp & Sarkis, 2016), AHP (Torres-Ruiz & Ravindran, 2018) and Fuzzy AHP (Liu et al., 2019) are the ability to model quantitative and qualitative criteria as well as categorize the supplier's overall performance into groups defined by fuzzy linguistic terms. The results of categorization can help guide supplier development initiatives as it groups suppliers with similar performance to indicate those needing improvement.

7 Conclusion

Sustainability evaluation cannot be based only on profit and other economic results, but also on environmental and social outcomes. Unlike financial records that are based on standardized procedures that have evolved since the emergence of large corporations in the late nineteenth century, environmental and social metrics are not consolidated in companies. In this way, their assessments are often made in a qualitative way, based on judgments of experts, with the presence of uncertainty and imprecision.

This paper has proposed a supplier sustainability assessment model based on fuzzy 2-tuple linguistic representation. The results of this study showed that the fuzzy 2-tuple linguistic representation is an interesting alternative for the evaluation of suppliers based on the TBL criteria. The use of fuzzy variables with common linguistic terms facilitates the evaluation of the criteria through the judgment of the decision makers. Aggregation by the weighted average operation allows the assignment of different weights for each criterion; moreover, its development is simpler and faster than fuzzy rules-based systems. The use of a fuzzy inference system (FIS) would be impractical in the context of the case study, with 13 criteria evaluated by sets of 7 linguistic terms, as this would generate a rule base with 7^{13} rules. The 2-tuple aggregation is performed in a continuous domain, represented by β ; therefore, the operation is performed without loss of information, different from the solutions based on symbolic methods or on extension principle.

During the case application of an agricultural product manufacturer, the experts did not present difficulty performing the evaluations using the 7 linguistic terms adopted in the model. They understood the basic mechanisms of the method, such as fuzzification, aggregation, and defuzzification. The final results of the models were considered coherent with the opinion of the different actors involved in the supply process.

Further studies can apply the proposed model for sustainable supplier selection using quantitative and qualitative criteria since the fuzzy 2-tuple linguistic representation makes this possible. Further applications in supplier selection and sustainability evaluation can also test the use of Hesitant Fuzzy Linguistic Term Sets (HFLTS) to make expert judgments more flexible through linguistic expressions.

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