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Abstract: Sustainable supply chain management has received much attention from both academia and industry due to various issues such as economic stability, environment conservation, and social ethics. To improve the sustainable performance of a value chain, its members need to carefully select their suppliers in relation to their own strategy. Thus, an effective tool for sustainable supplier selection and evaluation is essential, which considers the triple bottom line (TBL) of economic, environmental and social aspects by means of criteria adapted to the situation analysed. This paper develops a fuzzy decision tool to evaluate the sustainable performance of suppliers according to TBL. Sustainability criteria are identified to take into account the real hotspots in a food value chain. The proposed model integrates triangular fuzzy numbers (TFN), AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) in a novel way to consider quantitative and qualitative criteria as well as objective and subjective data. This is missing in most existing research when building their fuzzy models for supplier selection, but critical in dealing with the heterogeneous data available for TBL assessment. The application in a sustainable agrifood value chain illustrates the effectiveness of the proposed tool.

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Research Highlights:

- The sustainable criteria characteristics and the data types in use are discussed;
- Decision methods are analysed in terms of criteria and data types they deal with;
- A fuzzy decision tool is proposed to evaluate and group sustainable performance;
- The novel fuzzy AHP-TOPSIS model handles heterogeneous data;
- The proposed tool is verified by a sustainable agrifood case in France.

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Abstract: Sustainable supply chain management has received much attention from both academia and industry due to various issues such as economic stability, environment conservation, and social ethics. To improve the sustainable performance of a value chain, its members need to carefully select their suppliers in relation to their own strategy. Thus, an effective tool for sustainable supplier selection and evaluation is essential, which considers the triple bottom line (TBL) of economic, environmental and social aspects by means of criteria adapted to the situation analysed. This paper develops a fuzzy decision tool to evaluate the sustainable performance of suppliers according to TBL. Sustainability criteria are identified to take into account the real hotspots in a food value chain. The proposed model integrates triangular fuzzy numbers (TFN), AHP (Analytic Hierarchy Process) and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) in a novel way to consider quantitative and qualitative criteria as well as objective and subjective data. This is missing in most existing research when building their fuzzy models for supplier selection, but critical in dealing with the heterogeneous data available for TBL assessment. The application in a sustainable agrifood value chain illustrates the effectiveness of the proposed tool.

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Glossary

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANP	Analytic Network Process
DEA	Data Envelopment Analysis
ELECTRE	ELimination Et Choix Traduisant la REalité
FIS	Fuzzy Inference System
GA	Genetic Algorithm
LCA	Life Cycle Assessment
MCDM	Multiple-Criteria Decision-Making
MP	Mathematical Programming
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
SWOT	Strength, Weakness, Opportunity and Threat
TBL	Triple Bottom Line
TFN	Triangular Fuzzy Number
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

1 Introduction

Sustainability, as defined by the World Commission on Environment and Development, is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". A number of issues drive the development of sustainable supply chain management (SSCM), including economic stability, sharing economic value among supply chain actors, logistic optimisation to reduce global carbon footprint, environment conservation, social values and ethics, internal pressures for social responsibility and institutional pressures as the consequence of governmental/regulatory norms (Dubey et al. 2017). According to the research reviews of Zimmer, Fröhling, and Schultmann (2016), Ansari and Kant (2017) and Rajeev et al. (2017), the number of publications on SSCM has significantly increased during the last decade, which indicates the awareness and the importance of this topic.

Sustainable supplier selection and evaluation is one critical issue within SSCM faced by operations and purchasing managers (Seuring and Müller 2008). Sustainability influences the way that the suppliers are selected, which leads to rethinking the conventional supplier selection criteria. Environmental aspects such as emission pollutant, waste, reusability, biodegradable products and clean technologies are increasingly taken into account (Handfield et al. 2002, Humphreys et al. 2006, Raut 2011, Genovese et al. 2013). The triple bottom line (TBL) approach proposed by Elkington (1999) provides a systematic way to evaluate the suppliers' sustainable performance by considering economic, environmental and social dimensions.

Some researchers have adopted TBL to build their evaluation models. Dai and Blackhurst (2012) evaluated suppliers from a sustainability perspective by combining Analytic Hierarchy Process (AHP) with quality function deployment to consider the 'voice' of the stakeholders. Faramarzi et al. (2015) proposed a network Data Envelopment Analysis (DEA) model to measure the sustainable performance of cycle power plants. Trapp and Sarkis (2016) built a mathematical optimisation model for supplier selection and development considering the sustainability dimensions. The decision process associated with supplier selection has to handle high degrees of uncertainty. Therefore fuzzy set theory is often used. Ghadimi, Dargi, and Heavey (2017) designed a fuzzy inference system to select the most sustainable suppliers. Büyüközkan and Çifçi (2011) presented a decision framework for sustainable supplier selection under incomplete preference relations by using fuzzy scales in Analytic Network Process (ANP). Govindan, Khodaverdi, and Jafarian (2013) evaluated the sustainable performance of suppliers by integrating triangular fuzzy numbers (TFNs) in TOPSIS. Orji and Wei (2015) proposed a similar fuzzy TOPSIS model. Though sustainability has caught the attention of both academia and industry, there is still limited research on supplier selection and evaluation in light of all three dimensions (Govindan, Khodaverdi, and Jafarian 2013, Luthra et al. 2017). A gap exists in incorporating TBL into traditional operations strategies.

The sustainable assessment gets rather complicated due to the consideration of environmental and social criteria. In practice there is often a discrepancy between the available information and what would be ideally known. Therefore the assessment has to be based on the criteria that are available to be assessed, which have different characteristics. While some are based on solid numerical data, others require verbal expressions of judgements. However, the connection between the characteristics of criteria as quantitative or qualitative and the types of data used in the model as objective data or subjective judgements seems to be neglected in the existing selection tools, even though it affects the choice of the modelling method. Different methods handle different types of data. Methods like AHP can deal with both qualitative and quantitative criteria. AHP uses subjective judgements during the evaluation process, which leads to imprecision. Methods like TOPSIS and mathematical programming (MP) use numerical values and cannot work with qualitative criteria unless these are consistently converted to numerical values. Using fuzzy numbers to some extend solves the imprecision problem, but an overuse of fuzzy numbers under all criteria leads to objective data being ignored, as illustrated by the work of Wittstruck and Teuteberg (2012), Shen et al. (2013), Kannan, Jabbour, and Jabbour (2014) and Banaeian et al. (2018). There is a need for a decision tool to evaluate the sustainability, which can deal with heterogeneous data and the uncertainty involved in the evaluation process.

To narrow the gaps, this research has the following objectives: (1) to understand the sustainable criteria from the three dimensions in TBL; (2) to analyse the representative decision methods that can be used for sustainability evaluation; and (3) to propose a straightforward but practical tool to incorporate sustainability into supplier evaluation by taking into account different perspectives of value chain actors.

This paper develops a fuzzy decision tool to evaluate the sustainable performance of suppliers according to TBL by integrating TFNs, AHP and TOPSIS in a novel way, which is designed to handle both qualitative and quantitative criteria as well as subjective and/or objective data with the greatest possible flexibility. As supplier selection is often carried out collectively, the tool supports synthesising the judgements of multiple value chain actors. It further categorises the suppliers by analysing their strength, opportunity, threat and weakness. The applicability of the tool is demonstrated through a case study in an agrifood value chain. The research is based on four assumptions: (1) the decision makers understand the objectives, the criteria and the sub-criteria; (2) the decision makers have sufficient information and knowledge to judge the relative importance between every two criteria/sub-criteria; (3) the opinions of these decision makers are representative and of equal importance; and (4) the value chain actors have different perspectives on sustainability;

Section 2 presents the literature review on sustainable criteria and identifies the type of data that expresses these criteria. It also provides an overview of methods for supplier selection in general so that suitable approaches can be selected for TBL assessment. As many criteria can only be assessed through qualitative judgements, section 3 introduces TFNs to express these judgements. These are combined with an AHP-TOPSIS model in the tool described in section 4. Section 5 shows an application of the tool to the sustainable agrifood value chain. Section 6 concludes the paper.

2 Literature review

Criteria and decision-making methods are the two most important aspects of supplier selection process. This section reviews the suitable criteria for sustainable supplier selection. As the TBL approach combines economic, social and environmental concerns these will be addressed in turn. The tool presented in this paper combines multiple methods. They take fundamentally different approaches to how multiple criteria can be combined to select the best possible supplier. The methods discussed in the literature are either single assessment methods – using crisp or fuzzy values – or hybrid methods.

2.1 Sustainable criteria for supplier selection and evaluation

Conventional supplier selection and evaluation focuses on the performance of suppliers, which mainly reflects the economic concerns including product quality, cost, delivery, technology, production, service and geography. With the evolution of the buyer-supplier relationship from arm's length to strategic partnerships, new criteria have been considered such as 'financial conditions' (Pearson and Ellram 1995, Hsu et al. 2006), 'management and culture compatibility' (Hsu et al. 2006, Inemek and Tuna 2009) and 'communication ease' (Şen et al. 2008, Lee 2009). Table 1 lists a number of conventional supplier selection criteria.

[Table 1 near here]

With the awareness of environmental impact, many researchers have investigated the suppliers' environmental performance by various environment-related criteria (e.g. Handfield et al. (2002), Humphreys et al. (2006), Tsoulfas and Pappis (2008), Raut (2011)). Table 2 summarises several criteria from the literature. To select an environmentally friendly supplier with good economic performance, researchers include the environmental criteria into the conventional supplier selection to build a green supply chain (Büyüközkan 2012, Kannan et al. 2013, Tsui, Tzeng, and Wen 2014, Kumar, Jain, and Kumar 2014, Banaeian et al. 2018)

[Table 2 near here]

Social and green supplier development is necessary for sustainable supply chain management (Govindan, Khodaverdi, and Jafarian 2013). According to Ehrgott et al. (2011), the application of social criteria is an effective means of selecting suppliers as business partners with high strategic potential and accelerates learning in supply management functions. The social concerns come from internal aspect, i.e. the behaviour within an organisation, and external aspect, i.e. the effect of the organisation on society, as summarised in Table 3.

[Table 3 near here]

The sustainable criteria in Table 1 to Table 3 are extracted from research reviews, each of which covers various industries including electronics, automotive, chemicals and food (e.g. Hsu et al. (2006), Tsoulfas and Pappis (2008), Genovese et al. (2013), Zimmer, Fröhling, and Schultmann (2016)). Research on single industries (e.g. Şen et al. (2008) in electronics, Ghadimi, Dargi, and Heavey (2017) in automobile) and generic research (e.g. Bai and Sarkis (2010)) is also included. The criteria used in these publications highlight important aspects for advancing the consideration of sustainability in supplier selection. Indeed, they are still quite general (essentially derived from the recommendations of the ISO 26000 standards and the proposals of the Global Reporting Initiative). Most research does not take into account the characteristics of the criteria in the value chain being analysed. Criteria here are in reality rather than axes of work. It is then a question of effectively identifying the real criterion which can be a source of difficulty in a specific value chain. When executing such an exercise, the researcher is confronted with the heterogeneity of the types of criteria.

These criteria can be quantitative or qualitative. Quantitative criteria are those measured by numerical values which tend to be objective data and based on facts. For example, net price, air emission pollutant and standard working hours are generally expressed by numbers. Qualitative criteria are those measured by linguistic expressions. For example, technical capability, recycling capability and employment insurance are expressed by terms like 'high', 'medium' or 'low'. These expressions can be translated to numbers such as '5' for 'high', '3' for medium and '1' for low. Those numbers are subjective data based on experts' judgements.

In some cases, it is hard to say whether a criterion is definitely quantitative or qualitative, as this depends on how the decision maker perceives it and the available information. For example, if product reliability is defined by the percentage of conformance to design specification, it is quantitative; if it is perceived as level of conformance to design specification, it becomes qualitative. Also, a theoretically quantitative criterion can be expressed by subjective data. Take lead time for example. If a supplier only provides a duration in a range 7 to 14 days, a decision maker may use linguistic expressions to describe the offered performance and subjective data will be used. This influences the choice of the modelling methods. The modelling methods also decide what kind of data are required.

2.2 Modelling methods for supplier selection and evaluation

Sustainable supplier selection lies in the bigger context of supplier selection and therefore uses the same methods. Figure 1 presents a rough classification of the methods applied in the supplier selection literature.

[Figure 1 near here]

The methods fall into three categories: 'Individual methods' based on a single general decision-making technique; 'Fuzzy individual methods' using fuzzy set theory in a decision-making approach; and 'Hybrid methods' integrating several techniques. The methods can be further distinguished by the underlying techniques, including multiple-criteria decision-making (MCDM), MP, artificial intelligence (AI) and theory-based methods. MCDM provides a recommendation based on a finite set of alternatives by evaluating them under multiple criteria (Chai, Liu, and Ngai 2013). MP uses iterative algorithms that search every possible value and gradually achieve an approximate solution to a prescribed accuracy (Luenberger and Ye 2008), which is generally used for order allocation in supplier selection. The basic principle of the methods based on AI techniques for supplier selection is to train the system with historic data so that the choice can be deduced under similar situations. Theory-based methods are fuzzy set theory and grey theory. Both handle uncertainty and fuzziness of information in a range of domains.

Fuzzy set theory introduced by Zadeh (1965) is commonly integrated with another technique such as fuzzy MCDM and Fuzzy MP. One technique is fuzzy scales based on fuzzy numbers for subjective judgements, e.g., Lee (2009) and Chamodrakas, Batis, and Martakos (2010).

The use of hybrid methods compensates the disadvantage of each used method (Zimmer, Fröhling, and Schultmann 2016). Some research derives the weights of criteria, quantifies suppliers and/or allocates order by using different methods. For example, Wang, Cheng, and Huang (2009) obtained the criteria weights by fuzzy AHP and ranked suppliers by fuzzy TOPSIS. Ayhan and Kilic (2015) applied fuzzy AHP for supplier assessment and developed a mix integer linear programming model for order allocation. Hamdan and Cheaitou (2017) employed fuzzy TOPSIS for green supplier selection and a bi-objective integer linear programming method for allocation. Cheraghalipour and Farsad (2018) weighted criteria and suppliers by Best Worst Method and allocated the orders by a goal programming model. Some research employs one method to eliminate less qualified suppliers and assesses the remaining with other methods. Chen (2011) filtered the suppliers by DEA, the results of which were further evaluated by TOPSIS.

A robust decision model needs to handle heterogeneous data. To select a suitable approach, this research analyses several methods in each group according to what criteria are accepted and what kind of data they use for calculation.

The last column of Table 4 lists example research that has applied the corresponding methods. Most are from publications on sustainable supplier selection. Several highly cited articles (at least 10 citations/year since publication) in conventional supplier selection are also included, marked by 'C'. No article satisfying our citation criterion talked about TOPSIS as a single application, however it was used in combination with other methods.

[Table 4 near here]

Based on this analysis, this research chooses AHP and TOPSIS to build our model where TFNs are used as inputs to AHP and TOPSIS to handle the subjective judgement problem. AHP proposed by Saaty (1980) is widely applied to supplier selection because of its ease of use and nice mathematical properties (Handfield et al. 2002, Tahriri et al. 2008, Chan and Chan 2010, Lima-Junior and Carpinetti 2017). An important feature is that it can calculate the weights of criteria by pairwise comparison, while most other decision-making techniques cannot. AHP is applied in this research to structure the problem of sustainability evaluation in a hierarchal manner, following the TBL approach. It calculates the weights of the sustainable criteria by using fuzzy scales.

A generalisation form of AHP is ANP that considers the dependency among criteria and alternatives (Saaty 2001). ANP structures the problem in a network of elements (criteria and alternatives), clusters (collections of relevant elements) and connections (dependence between two elements from two different clusters or the same cluster, i.e. outer or inner dependence). For example, Razmi, Rafiei, and Hashemi (2009) incorporated fuzzy numbers with ANP for supplier selection and evaluation. Six criteria and four alternatives form three clusters where there are 12 dependences among criteria in their case. Amin-Tahmasbi and Alfi (2018) developed a fuzzy ANP model for green supplier ranking and a linear programming model for order allocation. They modelled the problem in a way similar to hierarchy, assuming that only inner dependences exist. 16 dependences are identified among fifteen sub-criteria in their study that those in the same group fully depend on each other. Although ANP has the advantage of taking dependency into weight calculation, it is not used in this research for the following reasons:

- Great dependency on decision makers for defining clusters and dependences. It requires the decision makers to have very sophisticated expertise and knowledge for grouping the relevant criteria and identifying the dependences properly. The results depend on their capability, which introduces more uncertainty. Different ways of defining them could lead to different results. The above two discussed studies have shown two network structures. Razmi, Rafiei, and Hashemi (2009) connected clusters through their outer dependence. Amin-Tahmasbi and Alfi (2018) connected clusters by adding a higher goal of green supplier selection.

- More efforts into calculation. The consideration of dependences and the use of supermatrix add the calculation efforts, especially when the number of dependences increases.
- Little dependency among the criteria in our case of sustainability evaluation. Dependency among the three categories of sustainable criteria has not been noticed during the case study. Also, it seems that little research on sustainability focuses on this dependency problem.

TOPSIS is a compromise decision-making technique, developed by Hwang and Yoon (1981). It cannot incorporate qualitative criteria unless judgements under these criteria are translated to numeric values. With this premise, TOPSIS can use both objective and subjective data during the calculation. However, as indicated in Table 4, existing tools based on fuzzy numbers and TOPSIS neglect this property and take subjective judgements for performance against all criteria, which leads to objective data being abandoned. The purpose of introducing fuzzy numbers in methods is to solve the imprecision problem. But an overuse of fuzzy numbers actually hampers this purpose. This research separates quantitative sustainability criteria that can use objective data from those qualitative ones that can use judgements.

3 TFNs for subjective judgements

Using TFNs in decision-making involves three issues – representing judgements, aggregating TFNs to synthesise judgements and defuzzifying a TFN to understand the results.

3.1 Representing subjective judgements in decision-making

A linguistic term is captured by a fuzzy set which consists two components, a set of elements

x and an associated membership function $\mu(x)$ (Klir and Yuan 1995). The membership function assigns to each element a value between 0 and 1 as its membership. A TFN, $\tilde{A}$, is a special class of fuzzy sets, which can be expressed as a triple (l, m, h) where l and h are the least and largest values with the smallest membership respectively and m is the value with the largest membership. The membership function of a TFN is defined as following and illustrated in Figure 2 (a).

$$\mu(x) = \begin{cases} (x-l)/(m-l), & l \le x \le m \\ (h-x)/(h-m), & \text{m} \le x \le h \end{cases}$$

[Figure 2 near here]

α-cut of a fuzzy set $\tilde{A}$, denoted as A_α, is a crisp value set containing all the elements with membership degrees greater than or equal to the specified value of α:

$$A_\alpha = \{x \mid \mu(x) \ge \alpha\}$$

The α-cut of a TFN can be represented as $A_\alpha = [l + (m-l)\alpha, h - (h-m)\alpha]$ as shown in Figure 2 (b), which helps defuzzify a TFN.

The algebraic operations on TFNs used in this research are as follows.

Addition: $\tilde{A}_1 \oplus \tilde{A}_2 = (l_1, m_1, h_1) \oplus (l_2, m_2, h_2) = (l_1 + l_2, m_1 + m_2, h_1 + h_2)$

Multiplication: $\tilde{A}_1 \otimes \tilde{A}_2 = (l_1, m_1, h_1) \otimes (l_2, m_2, h_2) = (l_1 l_2, m_1 m_2, h_1 h_2)$

$$\lambda \otimes \tilde{A}_1 = \lambda \otimes (l_1, m_1, h_1) = (\lambda l_1, \lambda m_1, \lambda h_1), \text{where } \lambda \text{ is a constant}$$

Reciprocal: $\tilde{A}_1^{-1} = (l_1, m_1, h_1)^{-1} = (1/h_1, 1/m_1, 1/l_1)$

In the evaluation models, there are two types of subjective judgements. One is the relative importance of one criterion over another and the other describes supplier performance against a criterion. Table 5 shows the TFNs for the subjective judgements in this research. For benefit criteria like quality, decision makers prefer a larger value whilst for cost criteria like price, smaller values are preferred.

[Table 5 near here]

3.2 Aggregating subjective judgements of multiple decision makers

One challenge of using subjective values is that judgements of different decision makers could vary. This is particularly important for judgements about sustainability which are highly contested. Therefore the tool aggregates multiple TFNs to a single TFN to synthesise multiple judgements and to determine the criteria weight in AHP by using the geometric mean. It has been proved as a proper way by Aczel and Saaty (1983) and Dong et al. (2010). Equation 1 synthesises the subjective judgements represented by n TFNs:

$$\tilde{A} = (l, m, n) = ((\prod_{i=1}^{n} l_i)^{\frac{1}{n}}, (\prod_{i=1}^{n} m_i)^{\frac{1}{n}}, (\prod_{i=1}^{n} h_i)^{\frac{1}{n}}) \quad (1)$$

3.3 Defuzzifying TFN

TFNs better captures the linguistic expressions, but crisp values are more intuitive to understand results. A TFN standing for a result need defuzzified. Yager's approach (1981) is adopted for defuzzification. With a fuzzy set $\tilde{A}$ of maximum membership α_{max} and its α-cut set A_α, the function $F(\tilde{A})$ calculates the crisp value associated with $\tilde{A}$ as equation 2, where $Ave(A_\alpha)$ is the mean value of the elements of A_α.

$$F(\tilde{A}) = \int_0^{\alpha_{max}} Ave(A_\alpha) d\alpha \quad (2)$$

For a TFN $\tilde{A} = (l, m, h)$ with its α-cut set $A_\alpha = [l + (m - l)\alpha, h - (h - m)\alpha]$, $F(\tilde{A})$ can be further calculated as:

$$F(\tilde{A}) = \int_0^{\alpha_{max}} Ave(A_\alpha) d\alpha = (l + 2m + h)/4 \quad (3)$$

Facchinetti, Ricci, and Muzzioli (1998) proved that this way of defuzzification considers both the worst and best results arising from a fuzzy number.

3.4 Checking fuzzy consistency

Though a TFN gives a certain tolerance on inconsistent judgement, a consistency check is still necessary because a big inconsistency may indicate a lack of understanding of the problem. According to Buckley (1985), the fuzzy comparison matrix $F=[\tilde{A}_{ij}]_{n\times n}$ is consistent if and only if:

$$\tilde{A}_{ik} \otimes \tilde{A}_{kj} \approx \tilde{A}_{ij} \quad (4)$$

The approximate equal '$\approx$' between two fuzzy numbers $\tilde{A}_1$ and $\tilde{A}_2$ whose membership functions are $\mu_{A1}(x)$ and $\mu_{A2}(x)$ respectively is defined as:

$$\min(v(\tilde{A}_1 \geq \tilde{A}_2), v(\tilde{A}_2 \geq \tilde{A}_1)) \geq \theta \quad (5)$$

Where $v(\tilde{A}_1 \geq \tilde{A}_2) = \sup_{x \geq y}(\min(\mu_{A1}(x), \mu_{A2}(y)))$ and θ is a fixed positive fraction less than or equal to 1. Literally speaking, $\tilde{A}_1$ and $\tilde{A}_2$ were approximately equal if $\tilde{A}_1$ is not greater than $\tilde{A}_2$ and $\tilde{A}_2$ is not greater than $\tilde{A}_1$.

In case of calculating fuzzy inconsistency ration with tolerance deviation, Mahmoudzadeh and Bafandeh (2013) has proved that if the comparison matrix obtained from α = 1 cut of $\tilde{A}$ is consistent, the original fuzzy comparison matrix is consistent. For a TFN $\tilde{A}$ = (l, m, n), its α = 1 cut reduces to a crisp number, i.e. $A_\alpha = m$. The consistency check of the fuzzy matrix $F=[\tilde{A}_{ij}]_{n\times n}$ becomes the check of the crisp matrix $F_{\alpha=1} = [m_{ij}]_{n\times n}$. Saaty's consistency ratio (*CR*) then can be used. A matrix with a *CR* less than 0.1 is considered as adequately consistent.

$$CR = CI/RI$$
$$CI = (\lambda_{max} - n)/(n-1) \quad (6)$$

CI is consistency index. λ_{max} is the max eigenvalue of the comparison matrix. *RI* is the random index whose value depends on the size of the matrix that can be looked up in Saaty (2008).

4 A Fuzzy AHP-TOPSIS model for sustainable performance evaluation

Based on the previous discussion, this research builds a Fuzzy AHP-TOPSIS model for sustainable performance evaluation, following a multi-step process.

Step1: Choose the criteria and assign weights to them. This step uses AHP to generate the weight. It can be carried out by multiple stakeholders and the tool automatically aggregates the results. The computational complexity of AHP is n^2 for n criteria due to pairwise comparisons. To reduce the computational complexity the three aspects of the TBL are addressed separately and weights are calculated separately.

Step2: assess individual suppliers against the criteria. This step is built on TOPSIS, where the actual performance characteristics are compared to ideal values predefined. TOPSIS have a computational complexity of $s \times n$. n is the number of criteria and s the number of suppliers

Step3: visualise the results by grouping the suppliers

Figure 3 gives an overview of the sub-steps with a simple example of three criteria and four suppliers. 'Criterion 1' and 'Criterion 3' are benefit criteria while 'Criterion 2' is cost criterion. Existing tools using TFNs, AHP and TOPSIS abandon objective data and take subjective judgements for performance against all criteria as indicated in Table 4. Our model uses both subjective and objective data for qualitative and quantitative criteria.

[Figure 3 near here]

4.1 Deriving the criteria weights by Fuzzy AHP

Fuzzy scales in Table 5 are applied during pairwise comparisons in AHP. It consists of the following sub-steps:

1a: establish the $n \times n$ fuzzy pairwise comparison matrix $F = [\tilde{c}_{ij}]$ for n criteria. $\tilde{c}_{ij} = (l_{ij}, m_{ij}, h_{ij})$ is a TFN representing the relative importance of criterion *i* over *j*.

1b: check the consistency of the fuzzy matrix. The consistency ratio of its corresponding crisp matrix $F_{\alpha=1} = [m_{ij}]$ is calculated by equation 6. If *CR* is less than 0.1, the matrix is consistent and then the process continues. Otherwise, the decision makers are asked to re-compare the criteria.

1c: synthesise the judgements if there are multiple decision makers. $\tilde{c}_{ij}^t = (l_{ij}^t, m_{ij}^t, h_{ij}^t)$ is the relative importance of criterion *i* over *j* judged by decision maker *t*. According to AHP, the relative importance of criterion *j* over *i*, is $1/\tilde{c}_{ij}^t$. The judgements are synthesised by equation 1 and the synthesised relative importance of *i* over *j* is as following, where *q* is the number of the decision makers.

$$\tilde{c}_{ij} = (l_{ij}, m_{ij}, h_{ij}) = ((\prod_{t=1}^{q} l_{ij}^t)^{\frac{1}{q}}, (\prod_{t=1}^{q} m_{ij}^t)^{\frac{1}{q}}, (\prod_{t=1}^{q} h_{ij}^t)^{\frac{1}{q}}) \quad (7)$$

1d: calculate the fuzzy weights of the criteria from the synthesised judgements. Equation 1 is used for the fuzzy weight $\tilde{w}_i$ of criterion *i* as shown below.

$$\tilde{w}_i = (l_i, m_i, h_i) = ((\prod_{j=1}^{n} l_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} m_{ij})^{\frac{1}{n}}, (\prod_{j=1}^{n} h_{ij})^{\frac{1}{n}}) \quad (8)$$

1e: obtain the crisp weights by defuzzifying the fuzzy weights. The weight of criterion *i*, w_i, is calculated by equation 9. If there are sub-criteria, repeat step 1 to 3, i.e. to establish the fuzzy pairwise comparison matrix with respect to each corresponding criterion, and then calculate their fuzzy local weights. By multiplying the weight of their parent criterion, their fuzzy global weights are derived. For the convenience in describing the model, $\tilde{w}_i$ is used to denote the fuzzy global weight, and w_i for crisp global weight.

$$F(\tilde{w}_i) = (l_i + 2m_i + h_i)/4 \\ w_i = F(\tilde{w}_i) \Big/ \sum_{j=1}^{n} F(\tilde{w}_j) \tag{9}$$

4.2 Evaluating the performance by Fuzzy TOPSIS

TOPSIS is applied to score the suppliers. Its principle is that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest distance from the negative ideal solution (NIS). In our model, objective data is used if they are available for quantitative criteria. Otherwise, TFNs for subjective judgements are used.

2a: establish the $m \times n$ decision matrix $T = [x_{ij}]$ with m candidate suppliers and n criteria. For quantitative criteria, x_{ij} is the objective data of the performance of supplier i against criterion j. For qualitative criteria, x_{ij} is the judgement of the performance from decision makers, which is firstly synthesised from fuzzy judgements of multiple decision makers and then defuzzified by equation 3. The scales for judgements refer to Table 5.

2b: normalise the decision matrix by linear normalisation by equation 10, where $x_j^* = \max_i x_{ij}$, $x_j^- = \min_i x_{ij}$, or set x_j^* as the aspired/desired level and x_j^- the worst level.

$$r_{ij} = (x_{ij} - x_j^-)/(x_j^* - x_j^-) \tag{10}$$

2c: construct the weighted normalised decision matrix $V = [v_{ij}]$. The criteria weights $w = (w_1, w_2, ..., w_j, ..., w_n)$ from step 1d are accommodated to the normalised decision matrix in step 2b.

$$v_{ij} = w_j \times r_{ij} \tag{11}$$

2d: determine the PIS A^* and NIS A^- solution by equations 12 and 13 respectively. J_1 represents benefit criteria set and J_2 is cost criteria.

$$A^* = \{(\max_i v_{ij} \mid j \in J_1), (\min_i v_{ij} \mid j \in J_2) \mid i = 1,2,...,m\} = \{v_1^*, v_2^*, ..., v_j^*, ..., v_n^*\} \tag{12}$$

$$A^- = \{(\min_i v_{ij} \mid j \in J_1), (\max_i v_{ij} \mid j \in J_2) \mid i = 1,2,..,m\} = \{v_1^-, v_2^-, ..., v_j^-, ..., v_n^-\} \tag{13}$$

2e: calculate the distances of each supplier to PIS and NIS by equation 14 and 15, denoted as D^+ and D^- respectively.

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \tag{14}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2} \tag{15}$$

2f: calculate the relative similarity C_i^* of each supplier with respect to the ideal solution by equation 16. The best is the one who has the maximum value.

$$C_i^* = D_i^- / (D_i^* + D_i^-) \tag{16}$$

4.3 Grouping the suppliers

The supplier on top rank is usually the best candidate but those with a close distance to the PIS could also be options. Analysing the suppliers in terms of their pros and cons enhances the understanding towards a suitable option.

3a: rank the suppliers according to the relative similarity C_i^* in descending order.

3b: group the suppliers to the following categories. C_i^* is a value within [0, 1], indicating how close a supplier's performance to PIS and how far to NIS. The closer it is to 1, the better a supplier performs. The closer to 0, the worse a supplier performs. When this value lies in the middle, it indicates a balance between the best and the worst. Thus, the unit interval [0,1] is divided into three ranges, and a supplier's performance is:

- 'Excellent', if $C_i^* \in [1, 0.67)$
- 'Acceptable', if $C_i^* \in [0.67, 0.33]$
- 'Poor', if $C_i^* \in [0, 0.33)$

3c: Profiling the suppliers based on their strength, weakness, opportunity and threat (SWOT). A SWOT matrix analysis is a planning method to analyse these four aspects at an organisation or business level by identifying the internal and external factors that influence the achievement of a business objective (Pickton and Wright 1998). This research uses the SWOT concept purely to supplier performance. The two dimensions of the matrix are the weight of criterion (the vertical dimension, indicating the importance of a criterion to the buyer) and the score of a supplier against a criterion (the horizontal dimension, indicating the performance under a particular criterion), as shown in Figure 4.

[Figure 4 near here]

For the vertical dimension, the range of weight w_j is [0, 1]. When there are n criteria, 1/n is the average value of weights since 1 is the sum of all the weights. 1/n is used as the division between 'low' and 'high'. Normalised performance r_{ij} (the performance of supplier i against criterion j) in Step 2b is used for score dimension because normalisation transforms the performance values of different units into a range [0, 1]. The midpoint 0.5 is taken to distinguish 'low' and 'high'. For benefit criteria, high value indicates good performance while for cost criteria, low value means good. To display them in the same matrix, the complement of r_{ij} is taken as the score r_{ij}' in horizontal dimension for cost criteria, i.e. $r_{ij}' = r_{ij}$ for benefit criteria and $r_{ij}' = 1 - r_{ij}$ for cost criteria. In this case, high score indicates better performance regardless the nature of criteria (i.e. benefit or cost). The suppliers are then plotted into four quadrants regarding the two dimensions:

- ***Strength***: $w_j \in [1/n, 1]$ and $r_{ij}' \in [0.5, 1]$. The criterion is important and the performance score is high. A supplier with more plotting points in this quadrant is preferred.
- ***Weakness***: $w_j \in [0, 1/n)$ and $r_{ij}' \in [0, 0.5)$. The criterion is not important and the score is low. This captures vulnerability of the supplier, but is of no particular importance to the buyer.
- ***Opportunity***: $w_j \in [0, 1/n)$ and $r_{ij}' \in [0.5, 1]$. The criterion is not important, but the score is high. It implies a potential advantage of a supplier if the buyer changes the priorities.
- ***Threat***: $w_j \in [1/n, 1]$ and $r_{ij}' \in [0, 0.5)$. The criterion is important but the score is low. To work with a supplier having more plotting points in this quadrant puts the buyer at risk.

The overall performance of a supplier is the result of weights multiplied by the scores. More plotting points in Strength and Opportunity quadrants could bring an excellent overall performance. More in Weakness and Threat quadrants leads to a poor overall performance. A supplier with its majority plotting points in Threat and Opportunity may have an acceptable performance because a low value in one dimension and a high value in the other provide an 'average' value to the overall performance. This SWOT profile is a complementary analysis to the overall performance grouping, providing a detail examination on each supplier. The suppliers can be ranked in each quadrant according to the numbers of their plotting points for a further comparison. Suppose two acceptable suppliers. The one with more plotting points in

Strength and Opportunity quadrants should be preferred, because it indicates more advantages of this supplier. The profile also implies where the supplier should improve. The performance under the criteria in Threat and Weakness needs improvement. Especially those in Threat should be focused on from the perspective of the buyer because these criteria are important to the buyer.

5 An application in a sustainable agrifood case

To facilitate the application and reduce the decision effort, the proposed model is implemented in a software tool programmed in Java. It was applied to evaluate the sustainable performance of famers in an agrifood case, which was studied over a period of three years in a research project at AgroParisTech in close collaboration with the companies involved (see, e.g., Petit et al. (2014), (2017), Kim, Cavusgil, and Calantone (2006), Petit, Bris, and Trystram (2017)).

5.1 Case description

The case concerns a value chain for sustainable pork meat in France. The value chain spans the activities from feeding pigs to delivering the meat and related products to consumers. It produces co-branded sustainable products and consists of two organisations. The upstream 'Agricultural cooperative', one of the major players in agrifood in France, includes the feed suppliers, the farmers, the slaughterhouses and transformers. The downstream 'Distribution cooperative' includes stockers and retailers. Both want to increase overall sustainable performance of the value chain, even though their interests and strategies differ. The identification of the criteria to be used to define supplier sustainability was obtained by crossing two sources. The first is a review of the scientific and technical literature dealing with the environmental, social and economic impacts related to the production, processing, distribution and consumption of French pork in France. This first work conducted in 2015 on the analysis of a hundred articles (many of which were in French given the specificities of the field of study, such as Nutrinoë (2015)) was then cross-referenced with the expectations and perceptions of stakeholders in the value chain. To this end, 10 semi-directive interviews were conducted with them and 20 scientific experts were also interviewed. This work made it possible to determine the hotspots specific to the value chain as well as to define the criteria describing them. On this base 20 criteria were selected as shown in Table 7. The environmental criteria were generated by Life Cycle Assessment (LCA) software (Simapro 8.0.5) from mapping the theoretical pork producing flows associated with each type of farmers. The LCA method determined the number of environmental criteria that should be considered by every type. The economic and social criteria are extracted from literature on the functioning and dysfunctions of these socio-technical systems in France. They were selected according to whether the criteria are suitable for the studied case. This has been realised by the confirmation of the stakeholders in the value chain as well as the scientific experts during the interviews. Whether data are available for these criteria was another consideration to determine the criteria. The details of generating the criteria and the data are explained in Petit, Bris, and Trystram (2017) and Petit et al. (2017).

Farmers who feed and supply pigs have an important role in achieving and maintaining the sustainability of the whole chain, because feed contributes significantly the economic, ethical and environmental burden in pig farming. Therefore the evaluation focusses on farmers. Farmers vary in animal feeding practices. Twelve types of farmers as listed in Table 6 are distinguished by their farming orientation (purchasing feed, producing feed, or a mix), dominant feed composition (colza, soy or corn), size of the feed system (<2500T or >2500T) and type of storage facility (horizontal or vertical).

[Table 6 near here]

5.2 Computational results

Three criteria in Table 7 are benefit criteria, i.e. C3_2: Biodiversity varieties, C3_3: Biodiversity species and C3_4: Localness, while the rest are cost criteria. The evaluation was carried out by people responsible for sustainability from both cooperatives.

[Table 7 near here]

One expert from Agriculture cooperative (DM1) and one from Distribution cooperative (DM2) participated in the evaluation process. They assessed the relative importance between the criteria differently due to the different interests of the two cooperatives. Figure 4 shows their comparisons which were transformed to the corresponding TFNs in Table 5. The consistency of their judgements has been checked. CR1 and CR2 under each matrix represent the consistency ratios of DM1 and DM2 respectively, which are all less than 0.1. The perspectives of the two cooperatives were aggregated by synthesising their priorities of the criteria by equation 7. The fuzzy weights were then calculated by equation 8 and translated to crisp weights by equation 9. The results are shown in Figure 5.

[Figure 5 near here]

The decision matrix is established and normalised by equation 10. Combined with the criteria weights, the weighted normalised matrix is constructed with equation 11. The distances to PIS and NIS of each type of farmers were calculated by equations 14 and 15 respectively. The final scores are obtained by equation 16. Figure 6 shows the results by our implemented software tool.

[Figure 6 near here]

The twelve types of farmers are ranked in descending order (>) and grouped to:

- Excellent: Bought colza (S1) > Bought soy (S2)
- Acceptable: Mix Vert (S10) > Made<2500T (S3) > Made>2500T (S4) > Mix Hori (S9)
- Poor: Mix maize Vert (S12) > Made maize Vert<2500T (S7) > Made maize Vert>2500T (S8) > Mix maize Hori (S11) > Made maize Hori<2500T (S5) > Made maize Hori>2500T (S6)

The farmers are further analysed by the SWOT matrix as illustrated Figure 7. The results are presented as follows, where the number of the plotting points in each quadrant of a supplier is shown in the brackets.

[Figure 7 near here]

- Strength: S1 (6), S2 (6) > S3 (3), S4 (3), S10 (3), S12 (3) > S7 (2), S8 (2)
- Opportunity: S9 (10), S10 (10) > S1 (9) > S2 (7) > S3 (5), S4 (5) > S5 (4), S6 (4), S7 (4), S8 (4) > S11 (3), S12 (3)
- Threat: S6 (6), S5 (6) > S11 (5), S9 (5) > S8 (4), S7 (4) > S12(3), S4 (3), S3 (3), S10 (3)
- Weakness: S11 (11), S12 (11) > S6 (10), S8 (10), S5 (10), S7 (10) > S4 (9), S3 (9) > S2 (7) > S1 (5) > S10(4), S9 (4)

5.3 Results discussion

The results show that purchasing feed (S1 and S2) is the best choice for the experts interviewed, whose scores are much higher than those of the rest types. Only considering the main dominant constituent, feed with corn not dominant is preferred over feed with corn dominant, i.e. S10, S3, S4 and S9 are in acceptable group while S12, S7, S8, S11, S5 and S6 are in poor group. Regarding the feed system, farmers equipped with silo<2500T have better performance than those with silo>2500T (i.e. S3>S4, S7>S8, S5>S6). Vertical storage facility (S10, S12 S7, S8) is overall better than horizontal ones (S9, S11, S5, S6).

The SWOT analysis further shows that purchasing feed (S1 and S2) is preferable that S1 and S2 have the majority of their plotting points in Strength and Opportunity quadrants (i.e. 15 and 13 respectively). Feed with corn not dominant (S3, S4, S9 and S10) could be alternative options that they have 8, 8, 11 and 13 plotting pints respectively in Strength and Opportunity quadrants and fewer points in Treats (i.e. 3, 3, 5 and 3 respectively). Feed with corn dominant (S5, S6, S7, S8, S11, S12) lowers down the sustainability of the value chain because the majority of their plotting points lie in Weakness and Threat quadrants (i.e. 16, 16, 14, 14, 16 and 14 points respectively). It also supports a close examination on each type of farmers. Take purchasing feed S1 for example. Although it has advantages on saving investment, cost and work hours (criteria: C2_1, C2_4, C2_5, C2_6, C2_7, C3_1), the performance on biodiversity and localness is rather poor (criteria: C3_2, C3_3, C3_4).

However, the high preference on purchasing feed seems contradict with that technical reports on pig feeding encourage the farmers to grow feed for the long run. This is mostly because of their outstanding performance on economic aspect that has a predominant weight (0.5964), though they perform quite poorly on social aspect and averagely on environmental aspect. Another reason is that the experts did not give much weight to territorial issues that favour local production. It indicates that despite the desire of value chain actors to improve the sustainable performance, economic consideration is still in a dominant position leading to a solution that does not maximise the performance on environmental and social aspects.

5.4 Managerial implications

Sustainability evaluation is a difficult exercise. The difficulty firstly comes from the criteria formulation and data collection. The general sustainability criteria presented in section 2 are across a variety of industries. They have to be adapted in particular case. Global Reporting Initiative (2013) advices the food sector to consider the evaluation in the context of a pork production, processing and distribution value chain. This led to the identification of more than 400 possible criteria. To adapt the criteria to our case we conducted literature review to identify specific hot spots in pork value chains and interviews with stakeholders and experts. The pre-selection of the criteria as listed in Table 7 was then confronted with the possibility of obtaining data to describe their conditions. We have been told that even Agricultural cooperative did not have the full data on their farmers in terms of all the preselected criteria. Agricultural cooperative and Distribution cooperative both had some data to estimate the sustainability, but did not share this with each other before. The tool encourages Agricultural cooperative to collect more information from their farmers as the tool compares them and shows which type of farmer is better with what type of configuration. This is also helpful to improve the performance of the whole value chain. It may also encourage the information exchange between the two cooperatives.

Another difficulty of sustainability evaluation lies in how to evaluate. Academically too complexity of a tool could lead to its abdication. The tool should be straightforward but practical to produce valid results. The underlying principle behind the proposed tool is acceptable to the managers and decision makers. The hierarchical display helps them to understand the problem of sustainability evaluation from the three dimensions of TBL. The graphical representations of the results may enhance managerial acceptance.

The tool helps different decision makers to reach a consensus about the weight of different criteria and therefore fosters a discussion about the relative importance of different aspects of sustainability. In the cases study the value chain had jointly committed to sustainable processes, but putting high weights on economic factors discarded options that would be more environmentally sustainable. The tool allows the users to reflect over their priorities and to establish the link between the weightings they place on certain factors and the solutions. For example in the case study, options with soya imported scored highly, because its feed cost was significantly lower than local alternatives. However the members of value chains might collectively decide not risking significant environmental damage, as the distraction of native rainforests to grow soya would pose. Results indicate that if a longer-term view is not taken, cooperatives risk not making the right choices because the short-term economic situation will necessarily prevail. Indeed, if all the food is imported the local eco-system is not maintained. The agricultural cooperative will become totally dependent on imports and their prices because there will no longer be structures able to feed the animals locally. It should therefore prioritise strategic criteria that consider not only current offers but also the risks.

Introducing the three dimensions into supplier evaluation is not only a way to select and monitor them, but also to make both organisations and suppliers aware of the importance of the sustainability criteria. This further introduces a continuous improvement approach with suppliers by highlighting the importance of these criteria.

5 Conclusions

SSCM has increased in importance during the last decade, making sustainable supplier selection and evaluation one of the most importance strategies. This paper focuses a decision tool to assess the sustainable performance of suppliers in light of economic, environmental and social criteria. A novel Fuzzy AHP-TOPSIS model has been proposed and applied in an agrifood value chain. The paper starts by analysing the sustainability criteria identified from the literature. This achieves the first research objective. The characteristics of criteria dictate the data that can be provided for them, which affects the choice of the decision methods. Representative methods are analysed in terms of their accepted criteria and data, which corresponds the second research objective. To combine qualitative and quantitative criteria as well as objective and subjective data this research chooses TFNs, AHP and TOPSIS for model development. Fuzzy AHP is used to derive the criteria weights and performance calculation is left for Fuzzy TOPSIS. This saves the efforts of decision makers on pairwise comparison in the throughout use of AHP. Meanwhile, unlike the existing fuzzy TOPSIS model, our proposed model retains the property of TOPSIS in using objective data. It is assumed that the value chain actors do not have a shared vision on sustainability. This has been shown in the case. The decision makers from the two organisations have emphasised different aspects of sustainability criteria. The tool synthesises different perspectives from decision makers, which supports achieving an aligned final decision. The application in the case evaluates the sustainable performance of the farmers of twelve feeding systems. Useful results have been generated with their ranks and belonging group.

The research assumes that the decision makers provide complete judgments on the relative importance between every two criteria. This is one limitation of this research because it is not always the case when dealing with practical problems. Decision makers may not have precise knowledge or is unable to discriminate the degree to which some elements are preferred than others (Herrera-Viedma, Alonso, et al. 2007, Herrera-Viedma, Chiclana, et al. 2007). How to repair incomplete judgement and incorporate this into sustainability evaluation is one future research work.

Another limitation is that all the decision makers are considered as equal important. These decision makers may have different capabilities since they come from different function departments, such as purchasing, financing, engineering and quality assurance. People from purchasing have better knowledge to compare the cost related criteria while those from quality assurance are more reliable to analyse the quality related criteria. Especially, what aspect, environmental, economic or social, is prioritised depends the strategy of an organisation, so people in higher management level have better vision. It is hard to judge which decision maker overall is more important than another. This research assigns a weight of 1 to each decision maker during the calculation. There are researchers who consider different weights of decision makers when synthesising their judgements. For example Ertay, Kahveci, and Tabanlı (2011) and Kar (2014) applied weighted geometric mean that the weights of decision makers are treated as the exponential in the aggregation formula. Büyüközkan, Karabulut, and Arsenyan (2017) multiplied the weights by a relaxation factor to estimate consensus degree of multiple judgements. However, these researchers assume the weights are given. Questions arise: (1) when decision makers judge the relative importance between criteria, who judges their importance; (2) when people have distinctive expertise, how to judge their importance. One possible solution is that the decision makers evaluate the part within their capabilities, and those of the same capability are weighted by their experience such as the working years, reputation and position in the department. To validate the solution and answer the two questions is another important piece of future work.

A third limitation is that, although the tool is designed to consider multiple decision makers, only two were involved in the case (i.e. one from Agriculture cooperative and one from Distribution cooperative) due to the constraint of time and effort. They were representatives of the two upstream and downstream value chain members, who knew well the perspectives, focuses and strategies of their organisations. However, it would be interesting to make more representatives in each organisation and other vale chain members participated in the evaluation. So their conflicts and common focuses can be identified and the results might be more general to the whole value chain. We are working on analysing different perspectives of more stakeholders for value chain sustainability.

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Table 1. Conventional supplier selection criteria (based on Dickson (1966), Pearson and Ellram (1995), Hsu et al. (2006), Şen et al. (2008), Inemek and Tuna (2009), Lee (2009), Bai and Sarkis (2010), Genovese et al. (2013), Fallahpour et al. (2017))

Criteria	Sub-criteria	Definition
Product quality	Product reliability	Consistent conformance to specification
	Defect rate	Percentage of unqualified parts
	Quality control system	The mature of the quality control system
Cost	Net price	Net price of the products
	Maintenance cost	The total cost for future maintenance
	Logistics cost	The total cost of transportation
	Order change & cancelation charge	The total charge for order change and cancelation
Delivery	Delivery reliability	The ability to meet the delivery schedules
	Lead time	The latency between the placement of the order and the arrival of the order
	Fill rate	The percentage of demand satisfied by inventory on hand
Technology	Design/co-design ability	The design/co-design capability to meet the requirements
	Technical capability	The mature of supplier's technical capability
	Manufacturing capability	The level of supplier's manufacturing capability
Production	Production capacity	The production capacity
	Production/manufacturing facility	The status of the supplier's production/manufacturing facility
Service	Repair service	The level of provided service
	Responsiveness	The efficiency and effectiveness of the supplier to response to a change
Geography	Geographical location	The closeness in geographical distribution
Market	Local market knowledge	The local market knowledge
	Speed to market	The speed that the supplier puts the product to market
Finance	Financial conditions	The financial position
	Financial assets availability	Financial assets availability to put into the partnership
Organisational management	Management status	Current management and organisation status
	Management & culture compatibility	Management style and organisation culture compatibility with buyer
Communication	Communication ease	The accessibility to the communication system
Attitude	Procedural compliance	Compliance or likelihood of compliance with the buyer's procedures (both bidding and operating)
	Commitment and trust	The reliability of the commitment and the trust on the supplier

Table 2. Environmental criteria for supplier selection (based on Humphreys et al. (2006), Tsoulfas and Pappis (2008), Bai and Sarkis (2010), Genovese et al. (2013), Govindan, Khodaverdi, and Jafarian (2013), Zimmer, Fröhling, and Schultmann (2016), Fallahpour et al. (2017), Ghadimi, Dargi, and Heavey (2017), Luthra et al. (2017))

Criteria	Sub-criteria	Definition
Environmental management system	ISO 14000 certifications	The environmental certifications the supplier holds
	Environmental policies and programs	The planning, implementing and auditing of the supplier's policies for environmental protection
Pollution control	Environmental remediation	The efforts the supplier puts on removing the pollution or containments from the environmental media
	End-of-pipe control	The effects the supplier processes the pollution or containments to reduce environmental damage
Resource consumption	Consumption of energy	The amount of consumption of energy during the measurement period
	Consumption of raw materials	The amount of consumption of raw materials during the measurement period
	Consumption of water	The amount of consumption of water during the measurement period
Pollution production	Production of air emission pollutant	Average volume of air emission pollutant per day
	Production of waste water	Average volume of waste water per day
	Production of solid wastes	Average volume of solid wastes per day
Eco-design	Reusability	The percentage of the product that can be reused
	Biodegradable products	The percentage of the product that is biodegradable
	Use of recycle materials	The use of recycle materials
	Use of hazardous materials	The use of hazardous materials
Green competence	Environmentally friendly packaging and labelling	The capability of the supplier to take environmental considerations for packaging and labelling
	Green R & D and Innovation	The capability to innovate new cleaner technologies, processes and practices
	Recycling capability	The capability of recycling

Table 3. Social criteria for supplier selection and evaluation (based on Bai and Sarkis (2010), Govindan, Khodaverdi, and Jafarian (2013), Zimmer, Fröhling, and Schultmann (2016), Luthra et al. (2017), Fallahpour et al. (2017))

Categories	Criteria	Sub-criteria
Internal social criteria	The interests and rights of employees	Employee contract
		Employment insurance
		Employment compensation
		Standard working hours
		Overtime pay
		Freedom of association
	Health and safety	Health and safety incidents
		Health insurance at work
		Training for safety
		Providing appropriate equipment at work
		Annual number of accidents
	Supportive activities	Discrimination
		Growth at work
		Attention to religious and culture issues
		Equity labour sources
		Information disclosure
External social criteria	Local communities influence	Health
		Education
		Housing
		Infrastructure
		Regulatory and public service
		Social cohesion
	Stakeholders influence	Supporting community projects
		Procurement standard
		Partnership screens and standards
		Stakeholder empowerment
		Stakeholder engagement

Table 4. Analysis of selected methods

		Criteria accepted		Data used for calculation			Citations
		Quantitative	*Qualitative*	*Objective*	*Subjective*	*Note*	
Individual method	AHP	√	√	-	√		Handfield et al. (2002), Dai and Blackhurst (2012), Dey and Cheffi (2013),Chan (2003) (C)
	ANP	√	√	-	√		Bayazit (2006) (C), Sarkis and Talluri (2002) (C)
	ELECTRE	√	√	√	-	Criteria weights as input	Boer, Wegen, and Telgen (1998) (C)
	TOPSIS	√	conditioned	√	quantified		-
	General MP	√	conditioned	√	quantified		Trapp and Sarkis (2016), Ghodsypour and O'Brien (2001) (C), Ng (2008) (C), Ravindran et al. (2010) (C)
	DEA	√	conditioned	√	quantified		Azadi et al. (2015), Faramarzi et al. (2015), Yousefi et al. (2016)
	GA	√	conditioned	√	quantified		Ding et al. (2005) (C)
	FIS	√	conditioned	√	quantified	Fuzzy sets need predefined	Ghadimi et al. (2017)
Fuzzy individual method	Fuzzy AHP	√	√	-	√		Çifçi and Büyüközkan (2011), Noorul Haq and Kannan (2006) (C), Chan and Kumar (2007) (C), Chan et al. (2008) (C), Chen et al. (2010) (C), Lee (2009) (C), Chamodrakas et al. (2010) (C)
	Fuzzy ANP	√	√	-	√		Büyüközkan and Çifçi (2011), Tseng et al. (2011), Vinodh et al. (2011) (C), Pang and Bai (2013)
	Fuzzy ELECTRE	√	√	√	-	Criteria weights as input	Sevkli (2010) (C)
	Fuzzy TOPSIS	√	√	-	√		Banaeian et al. (2018), Govindan et al. (2013), Kannan et al. (2014), Orji and Wei (2015), Shen et al. (2013), Zhao and Guo (2014), Chen et al. (2006) (C), Boran et al. (2009) (C)
	Fuzzy MP	√	conditioned	√	quantified		Kumar, Vrat, and Shankar (2004) (C), Amid et al. (2006) (C), Amid, Ghodsypour, and O'Brien (2009) (C), Erginel and Gecer (2016) (C), Mirzaee et al. (2018) (C), Yücel and Güneri (2011) (C)
Hybrids	Fuzzy AHP & fuzzy TOPSIS	√	√	-	√		Awasthi et al. (2010), Wittstruck and Teuteberg (2012), Yazdani (2014), Büyüközkan and Güleryüz (2016) (C), Wang et al. (2009) (C), Zouggari and Benyoucef (2012) (C)
	AHP & MP	√	conditioned	√	quantified		Ghodsypour and O'Brien (1998) (C), Ting and Cho (2008) (C)
	DEA&TOPSIS	√	conditioned	√	quantified		Chen (2011) (C)

Table 5. Judgement scales for relative importance and performance

TFNs for relative importance		***TFNs for performance judgement***		
Importance Definition	*TFNs for importance*	*Linguistic expressions*	*Scales for benefit criteria*	*Scales for cost criteria*
Extreme (ES)	(8,9,9)	Extremely good (EG)	(7,8,8)	(0,0,1)
Intermediate (VVS)	(7,8,9)	Very good (VG)	(6,7,8)	(0,1,2)
Very strong (VS)	(6,7,8)	Good (G)	(5,6,7)	(1,2,3)
Intermediate (S+)	(5,6,7)	Medium good (MG)	(4,5,6)	(2,3,4)
Strong (S)	(4,5,6)	Fair (F)	(3,4,5)	(3,4,5)
Intermediate (M+)	(3,4,5)	Medium poor (MP)	(2,3,4)	(4,5,6)
Moderate (M)	(2,3,4)	Poor (P)	(1,2,3)	(5,6,7)
Intermediate (W)	(1,2,3)	Very poor (VP)	(0,1,2)	(6,7,8)
Equal (E)	(1,1,1)	Extremely Poor (EP)	(0,0,1)	(7,8,8)

Table 6. Types of farmers in the value chain

ID	***Type name***	***Farming orientation***	***Dominant feed composition***	***Size of the feed system***	***Type of storage facility***
S1	Bought colza	purchasing	colza	-	-
S2	Bought soy	purchasing	soy	-	-
S3	Made<2500T	producing	not corn (dry cereals)	silo <2500T	-
S4	Made>2500T	producing	not corn (dry cereals)	silo >2500T	-
S5	Made maize Hori <2500T	producing	corn (wet cereals)	silo <2500T	horizontal (corridor)
S6	Made maize Hori >2500T	producing	corn (wet cereals)	silo >2500T	horizontal (corridor)
S7	Made maize Vert <2500T	producing	corn (wet cereals)	silo <2500T	vertical (tower)
S8	Made maize Vert >2500T	producing	corn (wet cereals)	silo >2500T	vertical (tower)
S9	Mix Hori	mix	not corn (dry cereals)	-	horizontal (corridor)
S10	Mix Vert	mix	not corn (dry cereals)	-	vertical (tower)
S11	Mix maize Hori	mix	corn (wet cereals)	-	horizontal (corridor)
S12	Mix maize Vert	mix	corn (wet cereals)	-	vertical (tower)

Table 7. Criteria and performance data

	Criteria	ID	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
C1: Environmental	Freshwater eutrophication	C1_1	Kg SO2 eq	0.07	0.09	0.13	0.13	0.12	0.12	0.12	0.12	0.09	0.09	0.14	0.14
	Terrestrial acidification	C1_2	Kg SO2 eq	8.34	8.34	7.95	7.95	7.69	7.69	7.69	7.69	8.49	8.49	8.87	8.87
	Human toxicity	C1_3	kg1,4-DB eq	269.76	320.61	591.40	591.40	572.46	572.46	572.46	572.46	131.61	131.61	201.17	201.17
	Fossil depletion	C1_4	kg oil eq	26.82	29.35	25.46	25.46	24.52	24.52	24.52	24.52	22.52	22.52	29.67	29.67
	Water depletion	C1_5	m3	8.30	3.86	36.76	36.76	35.57	35.57	35.57	35.57	11.14	11.14	32.03	32.03
	Climate change	C1_6	Kg CO2 eq	180.65	207.37	200.90	200.90	178.83	178.83	178.83	178.83	191.31	191.31	195.77	195.77
	Land occupation	C1_7	m2a	394.83	541.61	836.52	836.52	692.57	692.57	692.57	692.57	531.14	531.14	458.12	458.12
	Freshwater ecotoxicity	C1_8	kg1,4-DB eq	1.44	1.22	2.15	2.15	2.29	2.29	2.29	2.29	1.63	1.63	2.38	2.38
	Marine ecotoxicity	C1_9	kg1,4-DB eq	199.72	129.25	432.22	432.22	412.53	412.53	412.53	412.53	84.26	84.26	93.35	93.35
C2: Economic	Investment <5 years	C2_1	€/ton	0	0	21	27	21	27	21	27	15	21	15	21
	Investment 5 to 9 years	C2_2	€/ton	0	0	14	18	14	18	14	18	10	14	10	14
	Investment 10 to 14 years	C2_3	€/ton	0	0	7	9	7	9	7	9	5	7	5	7
	Feed manufacturing cost	C2_4	€/ton	0	0	30	30	39	39	39	39	31.3	31.3	38.5	38.5
	Total feed system cost	C2_5	€/ton	249	255	267	267	259	259	259	259	260	260	254	254
	Waste	C2_6	%	0	0	1	1	5	5	5	5	1	1	5	5
	Labour cost	C2_7	€/kg	0	0	3	3	6	6	3	3	9.5	3	9.5	3
C3: Social	Work hours	C3_1	h/day	0	0	0.17	0.17	0.33	0.33	0.17	0.17	0.5	0.17	0.5	0.17
	Biodiversity varieties	C3_2	#/formula	1118	1102	2767	2767	1821	1821	1821	1821	3013	3013	2067	2067
	Biodiversity species	C3_3	#/formula	6	5.33	9.67	9.67	6.33	6.33	6.33	6.33	11.33	11.33	7	7
	Localness	C3_4	%/formula	6.50	9.00	84.1	84.1	65	65	65	65	51.46	51.46	15.10	15.10

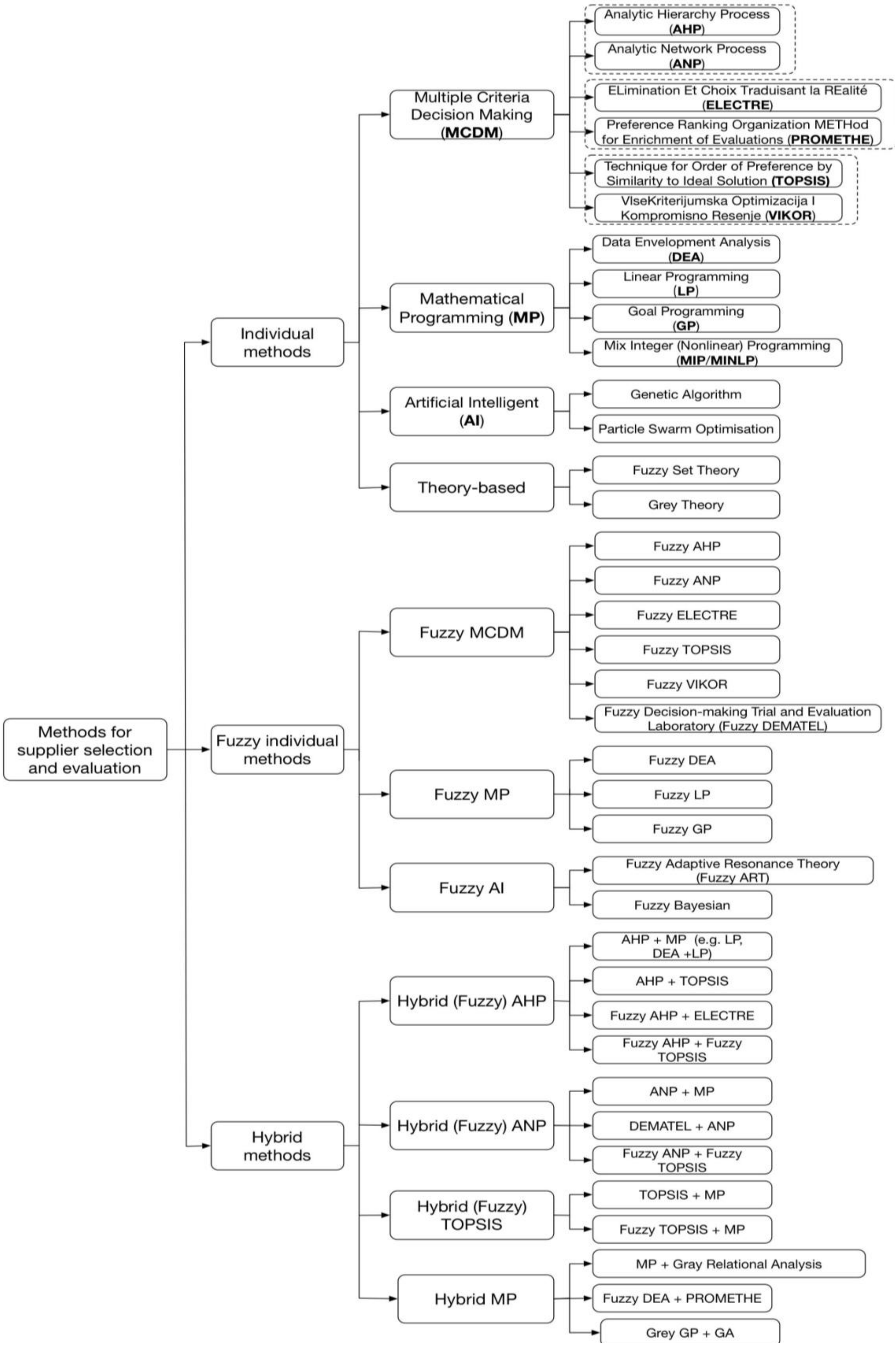


Figure 1. Classification of decision-making methods in supplier selection and evaluation, adapted from Ho, Xu, and Dey (2010), Chai, Liu, and Ngai (2013), Zimmer, Fröhling, and Schultmann (2016) and Karsak and Dursun (2016)

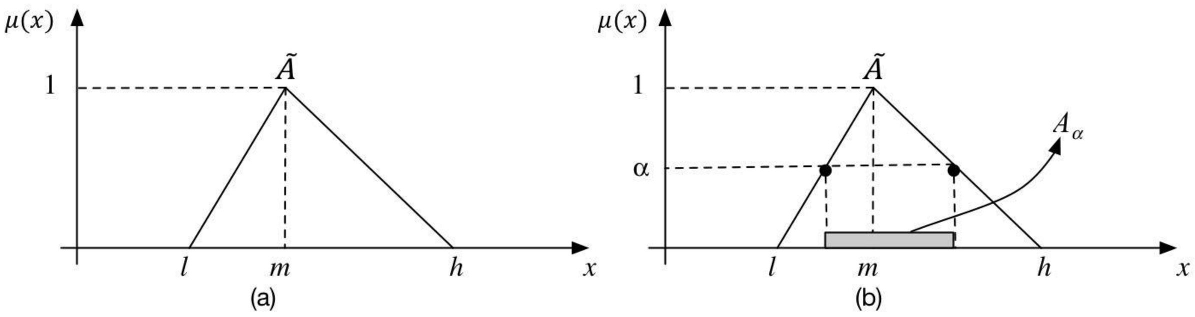


Figure 2. (a) TFN $\tilde{A}$; (b) α-cut of a TFN, A_{α}

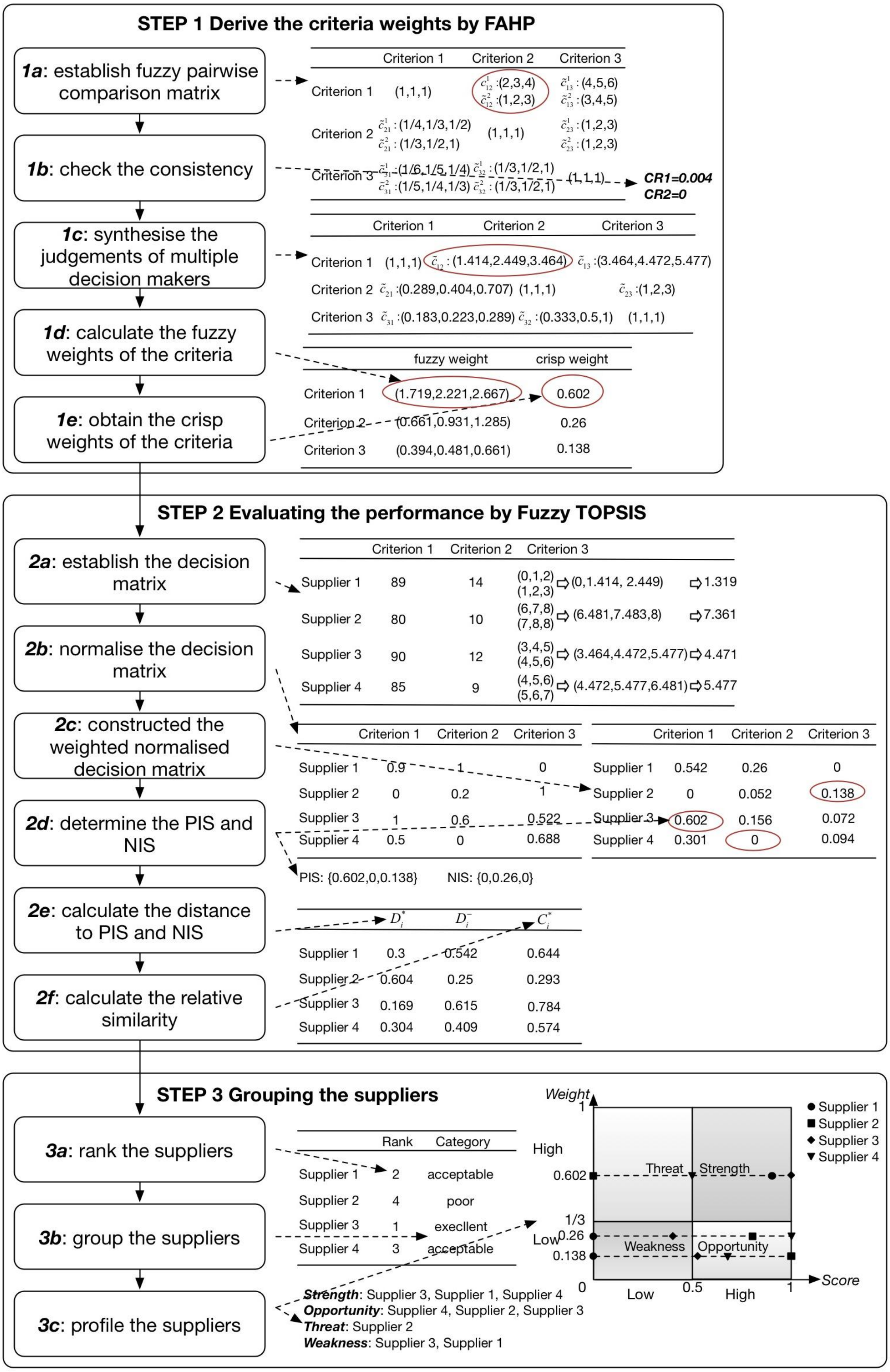


Figure 3. Fuzzy AHP-TOPSIS model

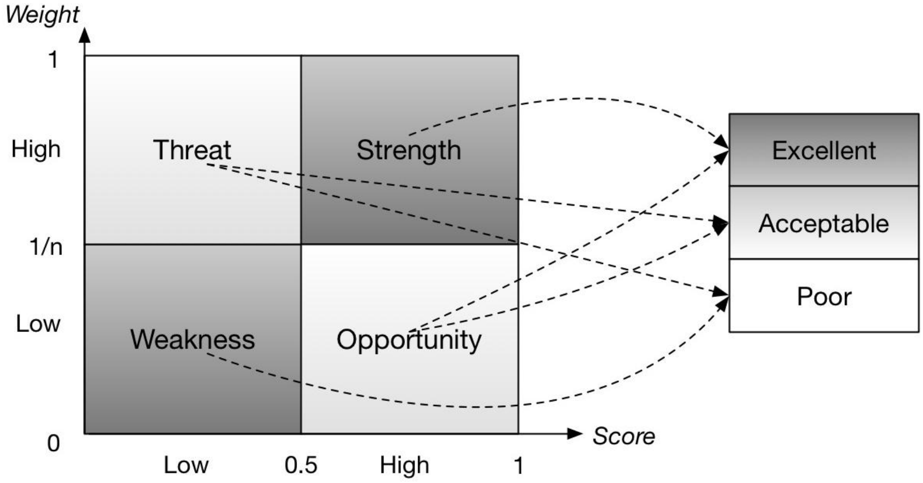


Figure 4. SWOT matrix regarding weight and performance score

		C1	C2	C3	Weight
C1	DM1	E	1/ES	E	0.2018
	DM2		E	E	
C2	DM1	ES	E	ES	0.5964
	DM2	E		E	
C3	DM1	E	1/ES	E	0.2018
	DM2	E	E		

CR1=0
CR2=0

(a)

		C1_1	C1_2	C1_3	C1_4	C1_5	C1_6	C1_7	C1_8	C1_9	Local weight	Weight
C1_1	DM1	E	E	1/VS	1/M	1/M	1/VVS	1/M	E	E	0.1216	0.0245
	DM2		VVS	VVS	VVS	VVS	VVS	E	E	E		
C1_2	DM1	E	E	1/VS	1/M	1/M	1/VVS	1/M	E	E	0.0431	0.0087
	DM2	1/VVS		E	E	E	E	1/VVS	1/VVS	1/VVS		
C1_3	DM1	VS	VS	E	M+	M+	1/S+	M+	VS	VS	0.1128	0.0228
	DM2	1/VVS	E		E	E	E	1/VVS	1/VVS	1/VVS		
C1_4	DM1	M	M	1/M+	E	E	1/M	E	M	M	0.0714	0.0144
	DM2	1/VVS	E	E		E	E	1/VVS	1/VVS	1/VVS		
C1_5	DM1	M	M	1/M+	E	E	1/M	E	M	M	0.0714	0.0144
	DM2	1/VVS	E	E	E		E	1/VVS	1/VVS	1/VVS		
C1_6	DM1	VVS	VVS	S+	M	M	E	M	VVS	VVS	0.1348	0.0272
	DM2	1/VVS	E	E	E	E		1/VVS	1/VVS	1/VVS		
C1_7	DM1	M	M	1/M+	E	E	1/M	E	M	M	0.2017	0.0407
	DM2	E	VVS	VVS	VVS	VVS	VVS		E	E		
C1_8	DM1	E	E	1/VS	1/M	1/M	1/VVS	1/M	E	E	0.1216	0.0245
	DM2	E	VVS	VVS	VVS	VVS	VVS	E		E		
C1_9	DM1	E	E	1/VS	1/M	1/M	1/VVS	1/M	E	E	0.1216	0.0245
	DM2	E	VVS	VVS	VVS	VVS	VVS	E	E			

CR1=0.0353
CR2=0

(b)

		C2_1	C2_2	C2_3	C2_4	C2_5	C2_6	C2_7	Local weight	Weight
C2_1	DM1	E	E	E	1/S	1/S	1/S	E	0.1536	0.0916
	DM2		VVS	VVS	E	VVS	VVS	E		
C2_2	DM1	E	E	E	1/S	1/S	1/S	E	0.0544	0.0324
	DM2	1/VVS		E	1/VVS	E	E	1/VVS		
C2_3	DM1	E	E	E	1/S	1/S	1/S	E	0.0544	0.0324
	DM2	1/VVS	E		1/VVS	E	E	1/VVS		
C2_4	DM1	S	S	S	E	E	E	S	0.3419	0.2039
	DM2	E	VVS	VVS		VVS	VVS	E		
C2_5	DM1	S	S	S	E	E	E	S	0.1211	0.0722
	DM2	1/VVS	E	E	1/VVS		E	1/VVS		
C2_6	DM1	S	S	S	E	E	E	S	0.1211	0.0722
	DM2	1/VVS	E	E	1/VVS	E		1/VVS		
C2_7	DM1	E	E	E	1/S	1/S	1/S	E	0.1536	0.0916
	DM2	E	VVS	VVS	E	VVS	VVS			

CR1=0
CR2=0

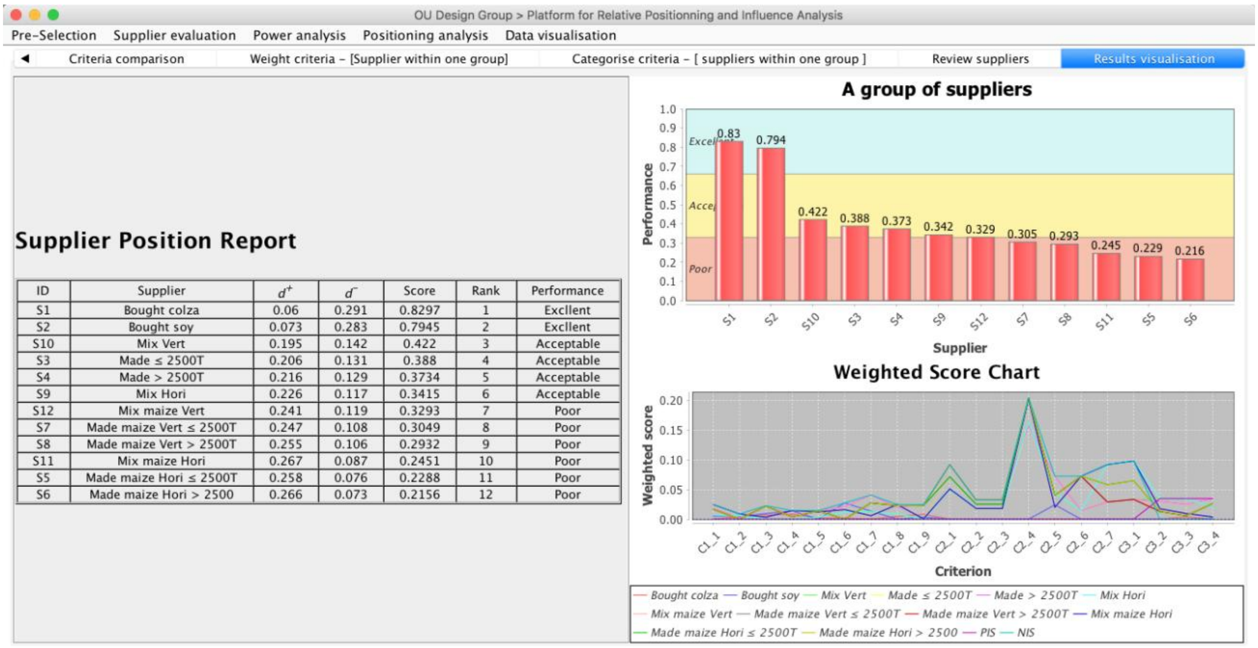
(c)

		C3_1	C3_2	C3_3	C3_4	Local weight	Weight
C3_1	DM1	E	VVS	VVS	VVS	0.4849	0.0978
	DM2		E	E	E		
C3_2	DM1	1/VVS	E	E	E	0.1717	0.0346
	DM2	E		E	E		
C3_3	DM1	1/VVS	E	E	E	0.1717	0.0346
	DM2	E	E		E		
C3_4	DM1	1/VVS	E	E	E	0.1717	0.0346
	DM2	E	E	E			

CR1=0
CR2=0

(d)

Figure 5. Pairwise comparisons and weights of (a) the three aspects, (b) the criteria under environmental aspect, (c) the criteria under economic aspect and (d) the criteria under social aspect



ID	Supplier	d^+	d^-	Score	Rank	Performance
S1	Bought colza	0.06	0.291	0.8297	1	Excllent
S2	Bought soy	0.073	0.283	0.7945	2	Excllent
S10	Mix Vert	0.195	0.142	0.422	3	Acceptable
S3	Made ≤ 2500T	0.206	0.131	0.388	4	Acceptable
S4	Made > 2500T	0.216	0.129	0.3734	5	Acceptable
S9	Mix Hori	0.226	0.117	0.3415	6	Acceptable
S12	Mix maize Vert	0.241	0.119	0.3293	7	Poor
S7	Made maize Vert ≤ 2500T	0.247	0.108	0.3049	8	Poor
S8	Made maize Vert > 2500T	0.255	0.106	0.2932	9	Poor
S11	Mix maize Hori	0.267	0.087	0.2451	10	Poor
S5	Made maize Hori ≤ 2500T	0.258	0.076	0.2288	11	Poor
S6	Made maize Hori > 2500	0.266	0.073	0.2156	12	Poor

Figure 6. Evaluation results

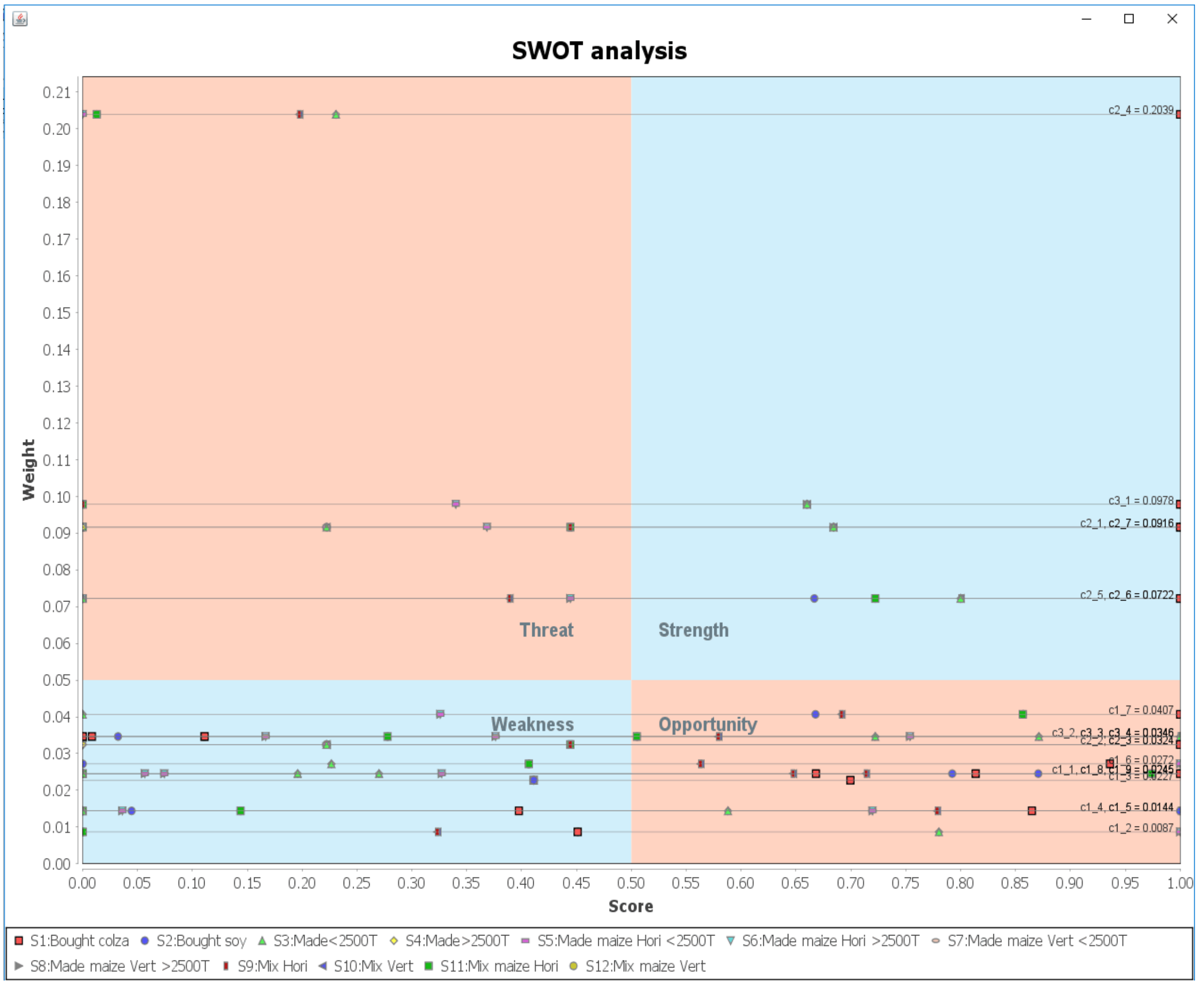


Figure 7. SWOT analysis of the farmers