# The suppliers' selection process through Extended Fuzzy Cognitive Maps and TOPSIS

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**Abstract**

In recent times, supplier selection has become one of the most important and crucial activities for companies. In this study, using the extended fuzzy cognitive maps (E-FCM) and technique for order of preference by similarity to ideal solution (TOPSIS), a decision-making support system is realized to assist managers in this activity. E-FCM expresses a causal relationship among criteria, computing linguistic variables to describe a complex situation. The proposed system allows managers to conduct *a priori* evaluation regarding supplier suitability, according to both company and market requirements. A panel of experts was formed, according to their expertise areas, to cover the entire problem domain and model it. The problem was investigated in terms of the factors identified by the experts, such as costs, delivery quality, organizational capability, supplier flexibility, service quality, and supplied product quality. These factors were analyzed using the TOPSIS approach to rank the suppliers, and the use of TOPSIS allows for discrimination of the E-FCM. This decision-making support system was applied to a real case scenario to test its functionality; in particular, an Italian shoes and accessories company. The TOPSIS ideal solutions were defined from two different points of view: based on the standard TOPSIS procedure and specifics fixed by the company managers. The two approaches resulted in considerably different outcomes, highlighting the need to consider concepts related to company expectations in the E-FCM.

**Keywords**: *Decision support systems; Extended fuzzy cognitive map; Supplier selection process; TOPSIS; Scenario analysis*.

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## 1. Introduction

In an era of global markets, the success of a business often hinges on the selection of the most appropriate suppliers. Supplier selection is often highly complex, as it encompasses a wide variety of unpredictable and uncontrollable factors that influence the decisions to be taken (van der Rhee et al., 2009). The aim of supplier selection is to identify the suppliers with the highest potential to meet company needs consistently (Araz et al., 2007). Supplier selection is a multi-criteria problem involving both tangible and intangible criteria, some of which may be conflicting, such as low price and high quality (Ustun and Demirtas, 2008). Therefore, supplier selection plays a crucial role in the success of the strategic goals of a company. At present, the changes in customer preferences, public procurement regulations, and new organizational procedures with increased decision-makers make the purchasing function complex and relevant for companies (De Boer et al., 2001). Another relevant topic in supplier selection is supply chain risk management, the attributes of which have recently been described by Rao et al. (2017). The authors propose a two-stage procedure for supplier selection, taking the supply chain risk into account. Scientists have dedicated considerable attention to supply chain vulnerability and risk. Wagner and Bode (2006) analyzed supply chain disruptions and vulnerability, highlighting how managers would benefit from broad supply chain knowledge to investigate supply chain behavior better. Proficient supplier management that begins with identifying potential suppliers is of central importance for the success of supply chain management (Lasch and Janker, 2005; Lin, 2009).

Furthermore, appropriate supplier selection significantly reduces purchasing costs and improves corporate competitiveness (Ghodsypour and O'Brien, 1998, Ciarapica et al. 2016). In particular, according to Garavelli (2003), the development and manufacturing of products require the support of a reliable supply chain. The overall project performance depends on the quality level of collaboration with the suppliers. A higher-quality level of activity coordination between the company and supplier improves the chances of the project success, by decreasing the costs and reducing the delivery delay risk (Tang and Tomlin, 2008; Crook and Combs, 2007, Ciarapica et al. 2019). However, dependency from suppliers may also become a threat to the company's success or production capability (Arend, 2006, Bevilacqua et al., 2015). For these reasons, it is essential to establish an effective supply chain, which becomes a crucial issue for any product development project.

This paper contributes to the resolution of the supplier selection problem, presenting an approach that combines extended fuzzy cognitive maps (E-FCMs) and the technique for order of preference by similarity to ideal solution (TOPSIS). The dynamic characteristics of a long-term relationship with suppliers are emphasized in order to realize a decision-making support system for supplier selection. The use of fuzzy linguistic variables can represent the state of each FCM concept. This allows the vagueness and imprecision of the information to be overcome and the model complexity to be reduced. The first advantage of E-FCMs is the ability to model decision problems graphically. This feature facilitates the validation process and promotes greater understanding by decision-makers. Moreover, the use of fuzzy labels allows for dealing with the uncertainty derived from subjective judgments (Görener et al., 2017). However, as asserted by Aggarwal (2017), in numerous real-life situations (such as negotiation processes), it is easier and preferable for experts to identify alternative-criteria evaluations in linguistic terms. According to Salmeron et al. (2012) and Baykasoğlu and Gölcük (2015), who used TOPSIS and FCM, TOPSIS adoption allows for an overall comprehension of the possible multiple outputs. However, in this study, TOPSIS is used jointly with an E-FCM, as non-linear relationships have been considered in certain specific situations.

In order to set the context, section 2 presents a bibliographical analysis of existing works regarding supplier selection. Section 3 presents the proposed research approach, where sections 3.1 and 3.2 explain the FCM theory and TOPSIS approach, respectively. Section 4 summarises the analyzed case study in terms of an Italian shoe factory. In particular, section 4.1 discusses the identification of the concepts that are relevant for supplier selection. Section 5 discusses the results according to the TOPSIS procedure, considering both the supplier and company points of view. Finally, section 6 analyses the research conclusions.

## 2. Supplier Selection Process

The latest research and experiments indicate a trend towards increased emphasis being placed on quality in supplier selection, mainly for small and medium enterprises. In particular, Johnsen (2009) defined the factors to be analyzed for the selection of the appropriate supplier as involving the following process: managers must select suppliers according to their innovative capability and complementarity. Primo and Amundson (2002) stated that managers must change their perception of supplier involvement in the decision-making process. Hitherto, managers have perceived supplier interaction as a barrier against fast and effective product development, probably owing to the uncooperative attitude of managers. According to this consideration, Luzzini et al. (2014) focused on the key design choices associated with the development of a vendor evaluation system (VES). In particular, they grouped the decision factors into three main categories: strategic alignment, process configuration, and execution. A performance evaluation system must be aligned with the company strategy, and supplier performances are no exception.

Moreover, the presence of suppliers in the decision process requires the collection of general information regarding them and continuous monitoring of their performances in terms of delivered products and services. This approach offers benefits to both the company and suppliers. In fact, the company increases its knowledge of suppliers, while the suppliers gain improved knowledge about the company decision-making process and its evaluation criteria. Bruno et al. (2012) highlighted the supplier willingness to take part in the definition process of methodologies for their evaluation in order to comprehend which factors affect the selection criteria and improve their position within the supply system. According to these observations, numerous studies have been developed to comprehend and deepen the supplier selection problem in terms of a decision-making approach. Büyüközkan and Göçer (2017) developed an intuitionistic fuzzy analytic hierarchy process to rank the set of available suppliers appropriately. Similarly, Chen and Zou (2017) provided a generalized intuitionistic fuzzy soft set combined with an extended grey relational analysis method to select an appropriate supplier with regard to risk aversion in the group decision-making environment. Bakeshlou et al. (2017) introduced green and sustainable supplier selection, combining a fuzzy analytic network process (ANP) and fuzzy multi-objective linear programming. In fact, according to Qin et al. (2017), green supplier selection and evaluation are essential for green supply chain management, which directly affects manufacturer performance. In their study, they solved the supplier selection problem considering a new distance calculation, based on the fuzzy logic and α-cuts of interval type-2 fuzzy sets. In the same manner, Gupta and Barua (2017) applied the best-worst method and fuzzy TOPSIS to select the optimal sustainable supplier, highlighting the fact that green innovation is fundamental for small and medium enterprises. Liu et al. (2108) combined ANP, the DEcision-MAking Trial and Evaluating Laboratory (DEMATEL) and game theory principles to obtain subjective and objective criteria weights and select suppliers appropriately. Zhong and Yao (2017) developed a supplier selection method based on the ELimination Et Choix Traduisant la REalité (ELECTRE) application, underlining the manner in which the criteria relevance still plays an essential role in the decision-making process and has a substantial impact on the results. As most decision-making methods refer to expert judgments and generally subjective, imprecise and vague information, the fuzzy set theory is commonly utilized. In particular, Özesmi and Özesmi (2004) asserted that fuzzy cognitive maps (FCMs) provide a unique methodology that can aggregate knowledge to represent a "scaled-up" version of individual knowledge and beliefs. Therefore, several approaches have been developed based on human participation, and certain researchers have developed FCM-based applications for the supplier selection problem. Hajek and Prochazka (2016, 2017) proposed an application based on interval-valued intuitionistic FCMs, exclusively concerning risk factors. Risk concepts have also been analyzed by Xiao et al. (2012), who used FCMs to describe the dependency and feedback among criteria derived by the preferential independent, and the ANP shortcomings. Moreover, they introduced the PSO learning algorithm for training in order to compensate for the FCM method dependence for expert advice in the reasoning process. Kar et al. (2017) combined an FCM and fuzzy decision map, forming a fuzzy decision network with fuzzy-TOPSIS, to identify the most flexible suppliers.

## 3. Research approach

The research approach has been developed in seven main steps that summarise the analysis aims and scope (see **Figure 1**). The first step, "**Problem Identification**", allows for a clear definition of the problem boundaries and expected outcomes. The second step, "**Experts Panel Establishment**" is essential for addressing the expert panel actions correctly. Each component of the panel must be selected according to the criteria of competence and area of expertise, as suggested by Clayton (1997) and Okoli & Pawlowski (2004). The function of the expert panel is to discover the main factors associated with the supplier selection problem. Subsequently, in the "**Concepts Identification**" and "**Relationships Identification**" steps, the experts are asked to express their opinions on the factors related to the identified problem and paired concept relations. By means of the bonds identification, this approach allows for distinguishing the main concepts from the secondary ones, playing a key role in the "**E-FCM Realisation**" step. Indeed, in the following "**E-FCM Refinement**" step, experts create clusters, grouping similar concepts referring to the same concept. Moreover, experts analyze the potential conflicts among the various concepts identified in the corresponding mental models.

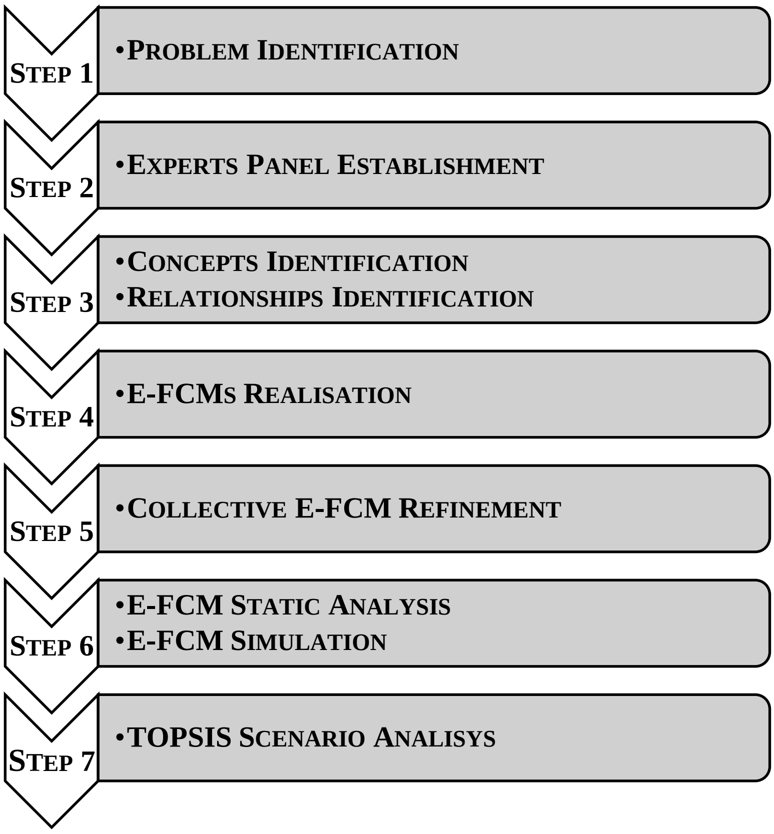


***Figure 1****: Research approach diagram*

Once the E-FCM for the supplier selection has been modeled and refined, it can be analyzed in order to identify the most relevant factors and possible hidden patterns, during the "**E-FCM Static Analysis**" step, as suggested by Bevilacqua et al. (2012). Thereafter, it is possible to simulate the system behavior in the "**E-FCM Simulation**" step (Bevilacqua et al., 2016, 2018). The E-FCM outcomes are analyzed in the "**TOPSIS Scenario Analysis**" in order to rank the available set of suppliers. In particular, in this step, the positive and negative ideal solutions have been defined according to the TOPSIS procedure, but also considering company expectations.

The novelty of this study relies on the application of E-FCM, as conditional weights have been considered for certain relationships. Therefore, conversely to the traditional FCM application, nonlinear weights have been defined to evaluate the relationship strengths.

### 3.1 Fuzzy Cognitive Maps

FCMs can be considered as fuzzy signed graphs with feedback (Stylios et al., 1997), reflecting mental processing and comprising of collected information and several cognitive abstractions that are individually filtered regarding physical phenomena and experiences (Axelrod, 2015).

FCMs are composed of nodes known as concepts, $C_i$, and interconnections $e_{ij}$ between concepts $C_i$ and $C_j$. A FCM models a dynamic complex system as a collection of concepts, and the cause-and-effect relations among concepts. The interconnections $e_{ij}$ among concepts are characterized by a weight $w_{ij}$ that describes the grade of causality between two concepts. Weights take values in the interval *[-1 1]*. Hitherto, simple FCMs have had edge values in {-1, 0, 1}, as proposed by Stylios and Groumpos (2004). In particular, the weight sign indicates the causality type. In fact, if $w_{ij} > 0$ between concept $C_i$ and $C_j$, a positive causality exists, which means that an increase in the value of concept $C_i$ will cause an increase in the value of concept $C_j$, while a decrease in the value of concept $C_i$ will cause a decrease in the value of concept $C_j$. Conversely, if a negative causality exists between two concepts, $w_{ij} < 0$; this means that the increase in the first concept involves a decrease in the value of the second concept, and a decrease in concept $C_i$ causes an increase in the value of $C_j$. In the absence of relationships among concepts, the value of $w_{ij}$ is 0. In summary, the value of the weight $w_{ij}$ indicates the strength of the relationship; that is, the degree of influence between concepts $C_i$ and $C_j$.

In order to define each relationships weight, experts answered to a specific questionnaire using a fuzzy Likert scale with ten values and, in the evaluation process, the collective value was derived from values lb (lower bound), mb (medium bound) and ub (upper bound) of the mentioned scale as shown in the following eq.

$$\frac{\sum_{i=1}^{n} x_i \, \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)}$$

where n is the number of experts, $\mu(x_i)$ is the membership value for the i-th expert evaluation $x_i$.

For example, by analyzing **Figure 2**, it is possible to see in (a) and (b) the fuzzified input 1 and 2 (i1 and i2), and the result is the grey trapezoid for each of them. The use of a specific fuzzy rule calculates the output fuzzy set, represented in step (c). It consists in the union of the two fuzzified inputs (the grey composed shaped) and the black point represents the center of gravity for the designed shape and its abscissa value (o1) is the numerical weight.

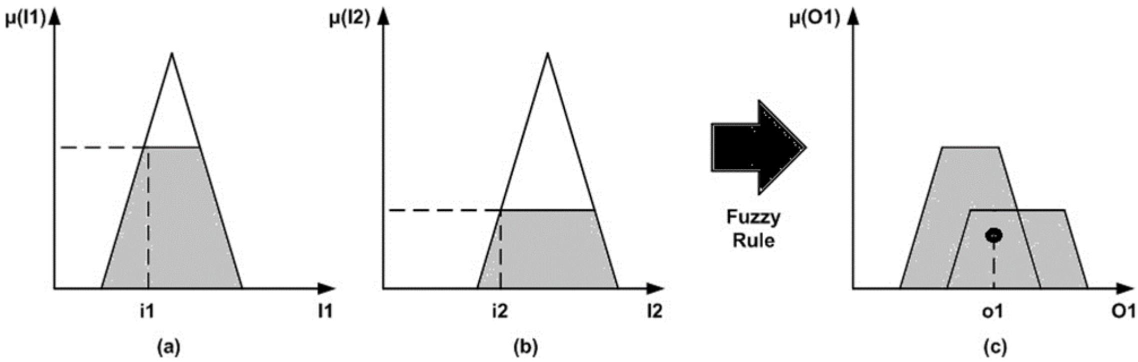


***Figure 2*** *Example of Center of Gravity method application*

The value of each concept is obtained by computing the influence of other concepts on the specific concept, by applying the mathematical rule expressed in equation (1), proposed by Kosko (1986):

$$A_i^{k+1} = f\left(A_i^k + \sum_{\substack{j \neq i \\ j=1}}^{n} A_j^k w_{ij}\right), \quad (1)$$

where $x_i(t)$ is the value of concept $C_i$ at time $t$; $x_j(t-1)$ is the value of concept $C_j$ at time $(t-1)$; $w_{ij}$ is the weight of the interconnection between concepts $C_i$ and $C_j$; n is the dimension of the concepts set; and $f(\cdot)$ is a characteristic threshold function (Bueno and Salmeron, 2009). It is highlighted that, in certain situations, it is important to take into account the precedent value of a concept (Stylios and Groumpos, 1999). In so doing, the new state vector holds the new values of the concepts following interaction among the map concepts. The interaction is caused by the change in the value of one or more concepts.

Commonly, the FCM dynamics are formed by its evolution in time, and they are modeled iteratively. Time has been considered as discrete, and the current value of each concept is computed by inspecting the previous iteration values. Thus, the update of each concept value for the present iteration must only occur after all concepts have been calculated. Evolving through time, the FCM may reach equilibrium, converging to a limit state, or following several numbers of iterations, according to the threshold function. However, it is important to note that "time" is an essential parameter to be contemplated in the FCM modeling phase.

FCM considers indicators such as the indirect and total effect, to allow for precise map analysis, as with cognitive maps (Bevilacqua et al., 2013). The indirect effect is defined by equation (2).

$$IE_k\left(C_i, C_j\right) = \min\left\{e\left(C_p, C_{p+1}\right\} \quad (2)$$

The calculus is based on reports of lower intensity; *($C_p$, $C_{p+1}$)* indicates the path (or paths) between concepts $C_p$ and $C_{p+1}$. In particular, $p$ and $p+1$ are indices of all the concepts that form the paths among nodes $C_j$ and $C_i$. Thus, the total effect (given by the relation of higher intensity) is expressed by equation (3).

$$TE(C_i, C_j) = \max\{I_k(C_i, C_j)\} \tag{3}$$

In particular: a directly proportionate total effect implies that each indirect effect is also directly proportionate; an inversely proportionate total effect implies that each indirect effect is also inversely proportionate; an indeterminate effect implies that certain indirect effects manifest direct-proportional effects, while others manifest inversely proportionate effects (Kosco, 1986). All the mentioned functions have been realized and executed in Matlab. The programming code has been reported in Appendix A.

### 3.2 Topsis Process

In multi-criteria decision-making (MCDM), several alternatives must be evaluated and compared, considering different criteria (Pedrycz et al., 2011). Thus, MCDM aims to provide support to decision-makers. Practical problems are generally characterized by numerous conflicting criteria, and there may exist no solution able to satisfy all of these simultaneously. Therefore, the solution is a compromise of the decision-maker preferences. For this reason, TOPSIS is based on the concept that the selected alternative must have the shortest distance from the positive ideal solution, and the furthest from the negative ideal solution. The final ranking is obtained by evaluating the closeness index (García-Cascales and Lamata, 2012). The TOPSIS procedure consists of the following steps:

1. Create an evaluation matrix, $Z$, composed of $m$ alternatives ($A_i$) and $n$ criteria ($C_i$), with the intersection of each alternative and criteria expressed as $z_{ij}$, as shown in equation (4).
2. 

$$Z = (x_{ij})_{mxn} = \begin{matrix} \\ A_1 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 & \dots & C_n \\ \begin{pmatrix} z_{1,1} & \cdots & z_{1,n} \\ \vdots & \ddots & \vdots \\ z_{m,1} & \cdots & z_{m,n} \end{pmatrix} \end{matrix} \tag{4}$$

3. The matrix $Z$ is then normalized to form the matrix $R$, as shown in equations (5) and (6).

$$R = (r_{ij})_{mxn} = \begin{matrix} & C_1 & \dots & C_n \\ A_1 & r_{1,1} & \cdots & r_{1,n} \\ \vdots & \vdots & \ddots & \vdots \\ A_m & r_{m,1} & \cdots & r_{m,n} \end{matrix} \tag{5}$$

$$r_{ij} = \frac{z_{ij}}{\sqrt{\sum_{i=1}^{m} z_{ij}^2}} \quad i = 1 \dots m; j = 1 \dots n \tag{6}$$

4. Calculate the weighted normalized decision matrix, *W*, according to the criteria weights $w_j$ provided by the experts, as shown in equations (7) and (8).

$$W = (w_{ij})_{mxn} = \begin{matrix} & C_1 & \dots & C_n \\ A_1 & w_{1,1} & \cdots & w_{1,n} \\ \vdots & \vdots & \ddots & \vdots \\ A_m & w_{m,1} & \cdots & w_{m,n} \end{matrix} \tag{7}$$

$$w_{ij} = r_{ij} \cdot w_j \quad i = 1 \dots m; j = 1 \dots n \tag{8}$$

5. Determine the positive ideal solution and negative ideal solution according to equation (9).

$$\begin{aligned} V^+ &= \{\max(w_{ij} \mid i = 1 \dots m) \mid j \in J^- \quad \min(w_{ij} \mid i = 1 \dots m) \mid j \in J^+\} \\ V^- &= \{\min(w_{ij} \mid i = 1 \dots m) \mid j \in J^- \quad \max(w_{ij} \mid i = 1 \dots m) \mid j \in J^+\} \end{aligned} \tag{9}$$

Specifically, if the considered criterion is a benefit (cost) concept, the relative value for the worst solution is the minimum (maximum) value among the alternatives values, and the optimal solution is the maximum (minimum) value.

6. Calculate the distances between the single alternative value, and both the positive ideal solution and negative ideal solution, as shown in equation (10).

$$\begin{aligned} d_i^+ &= \sqrt{\sum_{j=1}^{n} (w_{ij} - V_j^+)^2} \quad i = 1 \dots m \\ d_i^- &= \sqrt{\sum_{j=1}^{n} (w_{ij} - V_j^-)^2} \quad i = 1 \dots m \end{aligned} \tag{10}$$

7. Calculate the closeness index ($CL_i$) for the negative ideal solution according to equation (11) for each alternative, and rank the alternatives according to the calculated values.

$$CL_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{11}$$

In particular, $CL_i$ will be equal to 1 if and only if the alternative solution has the optimal condition, and 0 if and only if the alternative solution has the worst condition.

## 4. Case Study

The designed decision-making support system has been applied to a real case scenario in order to test and evaluate its functionality and validity. In particular, it has been used in the supplier selection stage of an important (in terms of market share and turnover) Italian shoes and accessories company. In the proposed model, the expert panel is composed of academic and non-academic experts. Specifically, the non-academic experts (seven in total: three suppliers, two logistics managers, and two customers) have a relevant background with supplier selection problems, and the academic experts (three in total) have long been studying the considered research subjects.

### 4.1 Extended Fuzzy Cognitive Map realization

In order to refine the main concepts referring to supplier selection, a questionnaire, which was developed analyzing the specific literature, was proposed to the expert panel. The questionnaire was realized using the Likert item scale. Specifically, according to Dawes (2008), five ordered response levels were used. The format of the applied five-level Likert items is: "Strongly disagree"; "Disagree"; "Neither agree nor disagree"; "Agree"; and "Strongly agree". Each expert modeled a personal FCM, identifying in total a number of concepts equal to 70. In order to comprehend the meaning of each concept, the experts described their identified concepts and relationships during the refinement step. The decision to refine the FCM, eliminating or grouping certain concepts (Cole & Persichitte, 2000), should be carried out after considering each of these in terms of the relevance of its removal from the map. At the end of this phase, the number of concepts was reduced to 36. **Table 1** displays the concept classification in terms of concept type and relative area of expertise. References for deepening the meaning of the concepts are reported in **Table 2**.

| Concept name | ID | Concept type | Area | Concept name | ID | Concept type | Area |
|---|---|---|---|---|---|---|---|
| Supplier competitiveness | C1 | Input | C | Corr. & prev. system quality[1] | C19 | Intermediate | OQ |
| Market competitiveness | C2 | Input | C | Continuous quality imp.[2] | C20 | Intermediate | Q |
| Cost reduction performance | C3 | Input | C | Quality accreditation and audit | C21 | Input | Q |
| Risk management costs | C4 | Input | COQ | Quality performance | C22 | Output | Q |
| Cost performance | C5 | Output | C | Financial stability | C23 | Input | O |
| Delivery flexibility | C6 | Intermediate | DF | Management quality | C24 | Input | O |
| Delivery perf.[3] | C7 | Output | D | Human resources quality | C25 | Intermediate | OS |
| Delivery reliability | C8 | Intermediate | CD | Innov. & learn. organisation[4] | C26 | Input | O |
| Compliance with a due date | C9 | Intermediate | DQS | Flexibility to change | C27 | Intermediate | OF |
| Compliance with product | C10 | Input | Q | State of the art technology | C28 | Intermediate | O |
| Compliance with price | C11 | Input | CDQ | Organization perf.[5] | C29 | Output | C |
| Compliance delivered q. | C12 | Input | CD | Tech and R&D support quality | C30 | Intermediate | S |
| Order to delivery LT | C13 | Input | D | R&D support | C31 | Input | S |
| Compliance with quality | C14 | Input | Q | Technological support | C32 | Input | S |
| Location position | C15 | Input | DO | Response to change | C33 | Input | FS |
| Quality data and reporting | C16 | Input | CQ | Ease communicate | C34 | Intermediate | S |
| Quality assessment level | C17 | Input | Q | Service performance | C35 | Output | S |
| Remedy for quality problem | C18 | Intermediate | Q | Flexibility | C36 | Output | F |

*1 Corrective & preventive system quality*
*2 Continuous quality improvement*
*3 Delivery performance*
*4 Innovative & learning organisation*
*5 Organisational performance*

***Table 1**: Identified concepts for supplier selection problem.*

| References | Costing (C) | Delivery (D) | Organisational (O) | Quality (Q) | Flexibility (F) | Service (S) |
|---|---|---|---|---|---|---|
| Atkinson et al., 2006 | | | *X* | *X* | | |
| Babu and Suresh, 1996 | | | | *X* | | |
| Bevilacqua et al., 2014 | | | | *X* | | |
| Bruno et al., 2012 | | | *X* | *X* | | |
| Chan and Kumar, 2007 | *X* | | *X* | *X* | *X* | |
| Dey et al., 2015 | *X* | *X* | *X* | *X* | | *X* |
| Globerson and Zwikael, 2002 | | | *X* | | | |
| Håkansson and Wootz, 1975 | | | *X* | | | |
| Klingebiel and Rammer, 2014 | | | *X* | | | |
| Rafati and Poels, 2015 | | | *X* | | | |
| Meredith and Mantel Jr, 2011 | *X* | | *X* | | | |
| Omurca, 2013 | | | | | | *X* |
| Platje et al., 1994 | | | | *X* | | |
| Sjoerdsma and van Weele, 2015 | | | *X* | | | |
| Stevenson and Sum, 2002 | | | | | | *X* |
| Wu and Barnes, 2010 | *X* | | | | | |

***Table 2**: References for deepening meaning of concepts.*

The single expert evaluations were transformed into numerical values using triangular functions. The final assessment was derived from the values $l_b$ (lower bound), $m_b$ (medium bound) and $u_b$ (upper bound) of the triangular functions, using equation (12).

$$e_i = \frac{\sum_{i=1}^{n} x_i \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)} \quad (12)$$

where $x_i$ is the assessment value (referring to $m_b$) and $\mu(x_i)$ is the relative membership function value.

Particular attention should be paid to the relationships C9→C8, C12→C8, C9→C22, and C12→C8, which justify the use of the E-FCM methodology. Indeed, their relative relationship strength values are dependent on specific conditions. They are not constant values, but rather "conditional weights". For example, considering concept C9 (compliance with a due date), according to the expert opinion, the delayed product delivery could imply an interruption during production, owing to product unavailability. In contrast, an anticipated delivery implies an increase in storage costs. Thus, if T* represents the due date for the delivery and T is the actual delivery date, the relationship strength between C9 and C8 (as well as between C9 and C22) is described by equation (13), where *ΔLT=T*-T*.

$$f(\Delta LT) = f(x) = \begin{cases} 0.22, & \Delta LT < 0 \\ 0.75, & \Delta LT \geq 0 \end{cases} \tag{13}$$

This means that a supplier who delivers early is superior to one who delivers late. Similarly, considering concept C12 (compliance with the product delivered), a smaller amount of delivered product could imply an interruption during production, owing to product unavailability. On the contrary, a greater amount of delivered product implies an increase in storage costs. Hence, if Q* represents the ordered product amount and Qd is the actually delivered quantity, the relationship strength between C12 and C8 (as well as between C12 and C22) is described by equation (14), where *ΔQd=Q*-Qd*. This means that a supplier who delivers more products is superior to one who delivers less. **Figure 3** shows the final collective E-FCM.

$$f(\Delta Qd) = \begin{cases} 0.73, & \Delta Qd < 0 \\ 0.19, & \Delta Qd \geq 0 \end{cases} \tag{14}$$

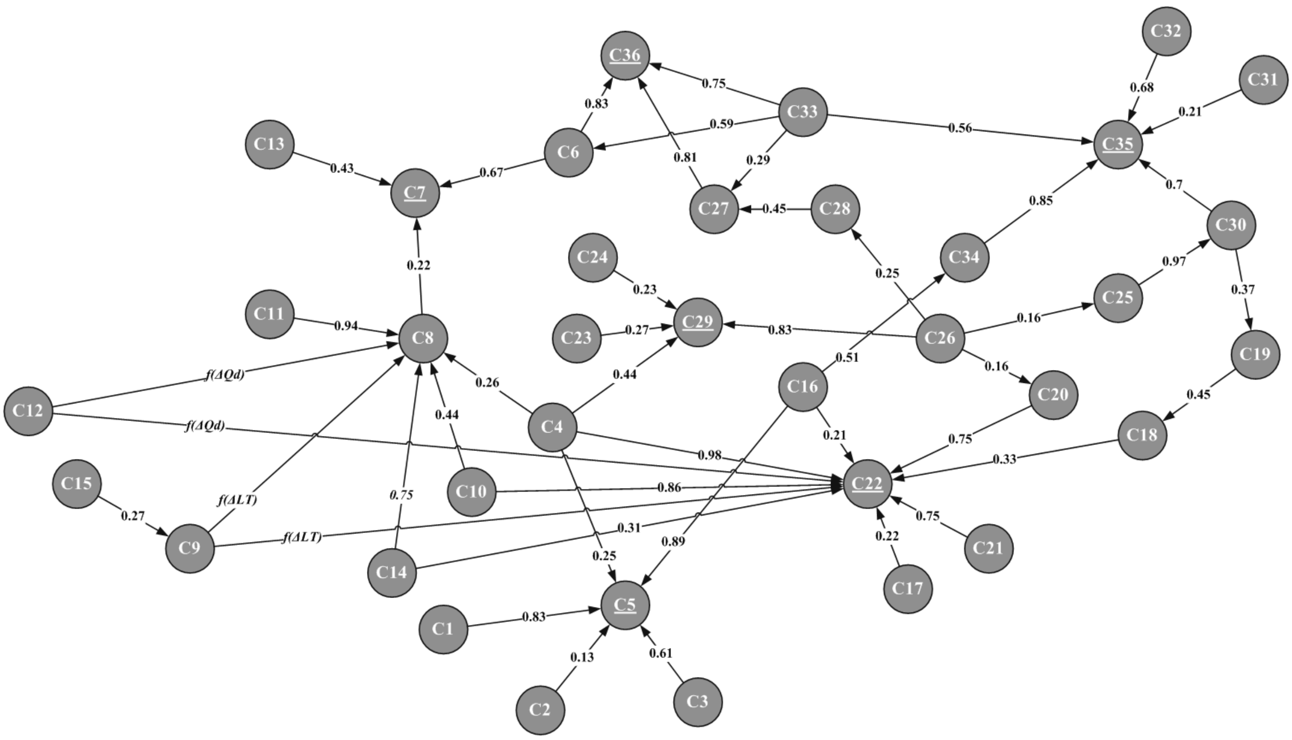


***Figure 3**: E-FCM for supplier selection problem*

At this point, according to Kandasamy and Smarandache (2003), each concept has been analysed to identify the relative fuzzy set to be used in the simulation.

## 5. Results and Discussion

**Table 3** displays the FCM structure analysis results, identifying the hidden patterns related to the connections of each concept with the FCM top event (or top events) considering their total effect (TE) values.

| N. | TE | HIDDEN PATTERN | N. | TE | HIDDEN PATTERN |
|---|---|---|---|---|---|
| **1** | 0,22 | C4 → C29 → C5 | **18** | 0,22 | C23 → C29 → C5 |
| **2** | 0,21 | C4 → C8 → C7 | **19** | 0,21 | C24 → C29 → C5 |
| **3** | 0,44 | C9 → C8 → C5 | **20** | 0,23 | C25 → C30 → C19 → C18 → C22 |
| **4** | 0,22 | C9 → C8 → C7 | **21** | 0,33 | C25 → C30 → C35 |
| **5** | 0,21 | C10 → C8 → C5 | **22** | 0,22 | C26 → C29 → C5 |
| **6** | 0,51 | C10 → C8 → C7 | **23** | 0,23 | C26 → C25 → C30 → C19 → C18 → C22 |
| **7** | 0,22 | C11 → C8 → C5 | **24** | 0,59 | C26 → C25 → C30 → C35 |
| **8** | 0,33 | C11 → C8 → C7 | **25** | 0,29 | C26 → C28 → C27 → C36 |
| **9** | 0,21 | C12 → C8 → C5 | **26** | 0,21 | C27 → C29 → C5 |
| **10** | 0,27 | C12 → C8 → C7 | **27** | 0,22 | C28 → C27 → C29 → C5 |
| **11** | 0,22 | C14 → C8 → C5 | **28** | 0,45 | C28 → C27 → C29 |
| **12** | 0,23 | C14 → C8 → C7 | **29** | 0,29 | C28 → C27 → C36 |
| **13** | 0,21 | C15 → C9 → C8 → C5 | **30*** | ***0,82*** | ***C30 → C19 → C18 → C22*** |
| **14** | 0,37 | C15 → C9 → C8 → C7 | **31** | 0,27 | C33 → C27 → C29 → C5 |
| **15** | 0,33 | C15 → C9 → C8 | **32** | 0,37 | C33 → C6 → C7 |
| **16** | 0,37 | C16 → C34 → C35 | **33** | 0,45 | C33 → C27 → C29 |
| **17** | 0,16 | C19 → C18 → C22 | | | |

* **Tech and R&D support quality** → **Corrective & preventive system quality** → **Remedy for quality problem** → **Quality performance**

***Table 3**: Hidden complex patterns and relative total effects.*

Hidden pattern number 30 is revealed as the most relevant among all of the identified hidden patterns, with a total effect equal to 0.82. This demonstrates the strong influence of the technological and R&D support quality on quality performance. Regarding this latter concept, hidden pattern number 17 demonstrates the scarce effect of corrective and preventive system quality, if the supplier cannot guarantee a suitable level of technological and R&D support quality. Thus, the combined analysis of the hidden patterns allows for determining more complex meanings regarding the identified concepts. In order to gain knowledge on the total effect of each concept on the others, **Table 4** demonstrates the impact of the starting node $C_i$ on the final node $C_j$ ($C_i \rightarrow C_j$), using the fuzzy scale provided by the experts.

| Connection | TE | Connection | TE | Connection | TE |
|---|---|---|---|---|---|
| C4→C22 | very strong | C16→C35 | medium | C26→C36 | weak |
| C25→C30 | very strong | C19→C18 | medium | C24→C5 | weak |
| C11→C8 | very strong | C28→C5 | medium | C24→C29 | weak |
| C16→C5 | very strong | C28→C27 | medium | C17→C22 | weak |
| C30→C22 | strong | C28→C29 | medium | C4→C7 | weak |
| C34→C35 | strong | C28→C36 | medium | C8→C7 | weak |
| C14→C8 | strong | C4→C5 | medium | C9→C7 | weak |
| C1→C5 | strong | C4→C29 | medium | C10→C7 | weak |
| C6→C36 | strong | C10→C8 | medium | C11→C7 | weak |
| C26→C29 | strong | C13→C7 | medium | C12→C7 | weak |
| C27→C29 | strong | C25→C18 | weak | C14→C7 | weak |
| C26→C5 | strong | C25→C19 | weak | C15→C7 | weak |
| C27→C5 | strong | C30→C18 | weak | C31→C35 | weak |
| C29→C5 | strong | C30→C19 | weak | C8→C5 | weak |
| C27→C36 | strong | C18→C22 | weak | C9→C5 | weak |
| C33→C36 | strong | C19→C22 | weak | C10→C5 | weak |
| C21→C22 | strong | C25→C22 | weak | C11→C5 | weak |
| C20→C22 | strong | C30→C22 | weak | C12→C5 | weak |
| C25→C35 | strong | C14→C22 | weak | C14→C5 | weak |
| C30→C35 | strong | C33→C5 | weak | C15→C5 | weak |
| C32→C35 | strong | C33→C27 | weak | C16→C22 | weak |
| C6→C7 | strong | C33→C29 | weak | C26→C18 | very weak |
| C12→C8 | strong | C23→C5 | weak | C26→C19 | very weak |
| C3→C5 | medium | C23→C29 | weak | C26→C22 | very weak |
| C33→C6 | medium | C15→C8 | weak | C26→C25 | very weak |
| C33→C7 | medium | C15→C9 | weak | C26→C30 | very weak |
| C9→C8 | medium | C4→C8 | weak | C26→C35 | very weak |
| C33→C35 | medium | C26→C27 | weak | C26→C20 | very weak |
| C16→C34 | medium | C26→C28 | weak | C2→C5 | very weak |

***Table 4**: Total effects evaluated for each concept on the others.*

**Table 5** displays the fuzzified values for the concepts with total effects greater than 0.5 on average (the TE mean value is indicated in brackets). It is important to note that the final two columns in **Table 5** report the signs of the evaluation parameters ΔLT and ΔQd, which is necessary for the strength definitions $f(\Delta LT)$ and $f(\Delta Qd)$ (see section 4.1).

| | C1 (0,83) | C3 (0,6) | C4 (0,47) | C6 (0,75) | C16 (0,53) | C20 (0,75) | C21 (0,75) | C25 (0,55) | C27 (0,82) | C32 (0,68) | C34 (0,85) | ΔLT | ΔQd |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sup 1** | M | M | M | VW | M | VW | M | VW | W | M | VW | + | + |
| **Sup 2** | M | M | M | VW | M | W | M | VW | M | M | VW | - | - |
| **Sup 3** | M | S | M | W | M | VW | M | VW | M | M | W | - | + |
| **Sup 4** | VS | VS | VS | M | S | VW | S | VW | W | S | W | + | - |
| **Sup 5** | M | S | VW | VW | S | M | VW | VW | W | VW | VW | + | + |
| **Sup 6** | W | M | W | VW | VW | VW | S | VW | M | VW | VW | - | + |
| **Sup 7** | S | S | S | VW | S | W | VW | W | VW | M | VW | - | - |
| **Sup 8** | W | VS | W | VW | W | W | VW | VW | VW | S | VW | - | - |

***Table 5**: Input fuzzy values used for scenario simulation.*

**Figure 4 - Figure 56** illustrate the system outcomes related to the output concepts. In particular, **Figure 4** underlines the manner in which all of the considered suppliers are characterized by a strongly positive evaluation regarding the costs and quality performance. Thus, according to these parameters, all of the suppliers can be regarded as suitable production partners. The supplier evaluation decreases if delivery and organizational performance are considered, as the marks range also considers medium values (see **Figure 5**). In contrast, regarding flexibility and service (see **Figure 6**), the supplier evaluations range within the entire set of possible marks, from very weak to very strong.

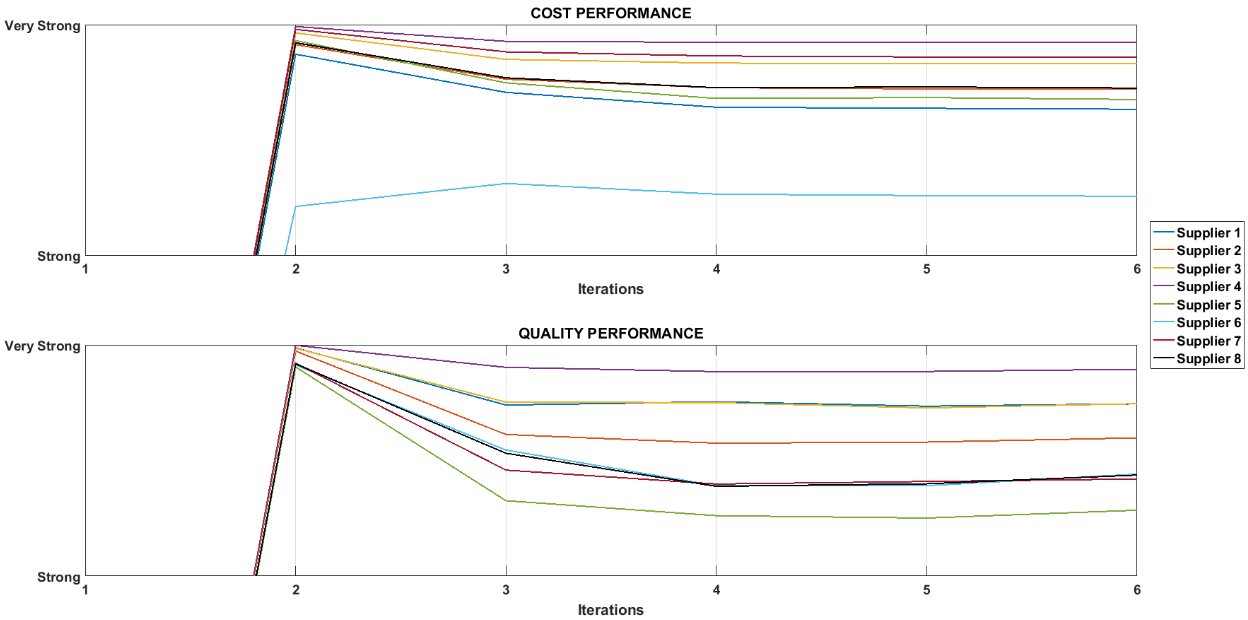


***Figure 4**: Cost and quality performance evaluation*

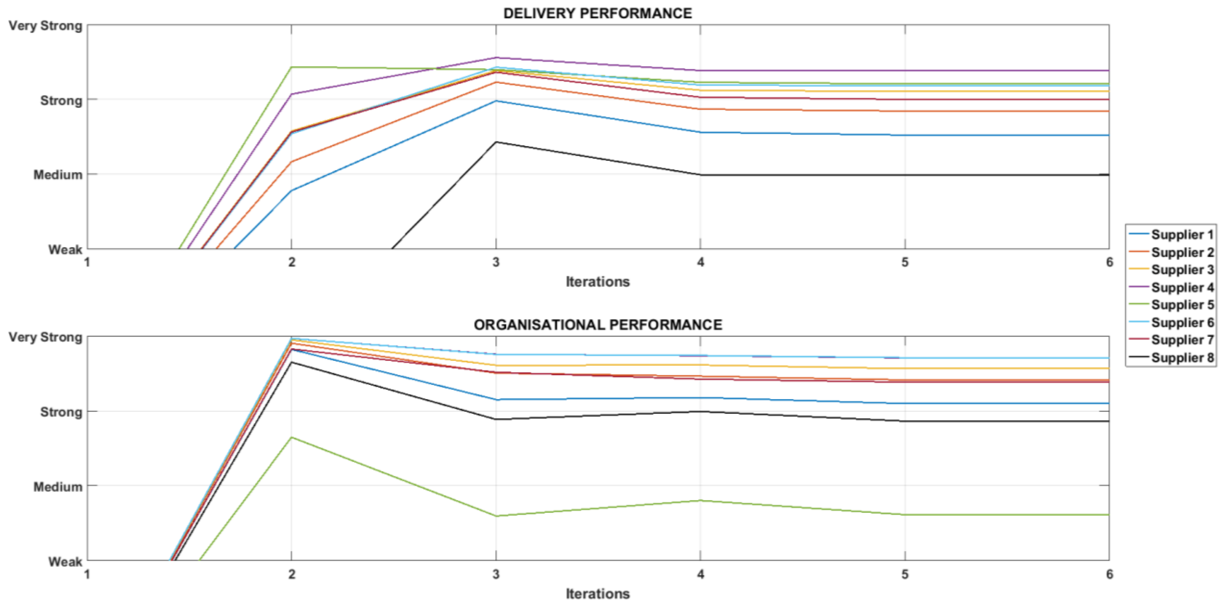


***Figure 5****: Delivery and organisational performance evaluation*

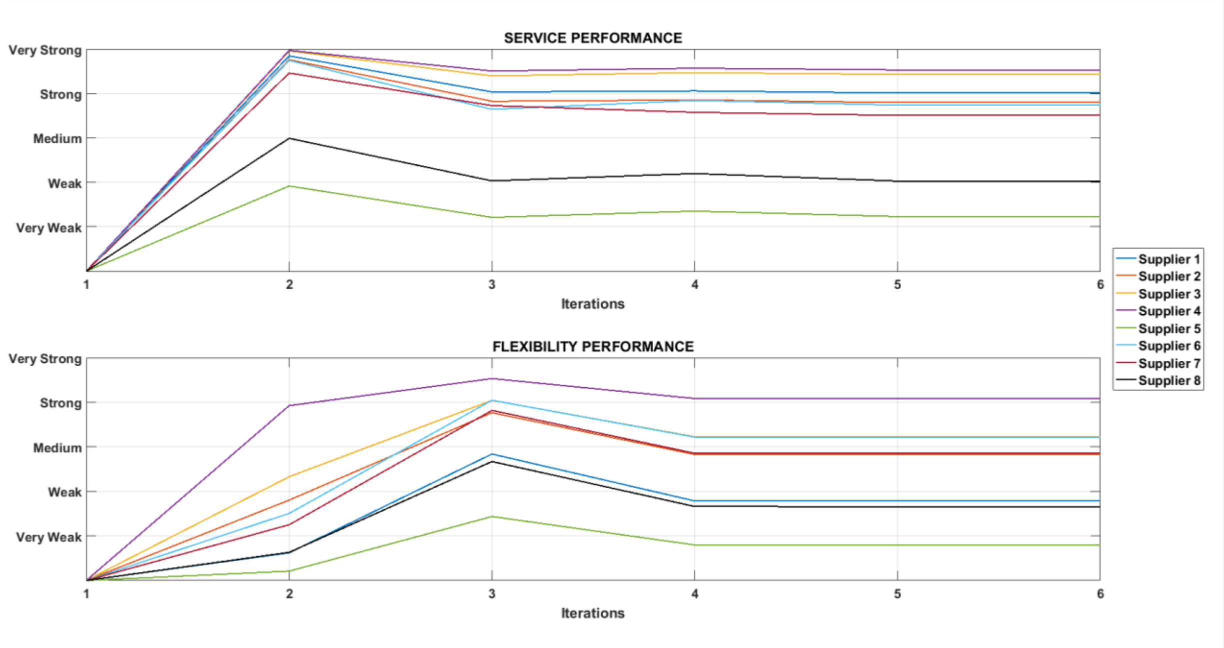


***Figure 6****: Service and flexibility performance evaluation*

In line with these results, it is not easy to identify the best supplier, considering all of these parameters, which is why the E-FCM outputs must be processed by a specific decision-making method such as TOPSIS.

### 5.1 Ranking supplier scenario with TOPSIS

Considering the TOPSIS procedure, explained in section 3.2, **Table 7** displays the normalized evaluation matrix derived from **Table 6** and considering the same relevance for each criterion. **Table 8** displays the positive ideal solution and the negative ideal solution obtained according to equation (9) and considered as "supplier point of view" solutions.

| | **C5** | **C7** | **C22** | **C29** | **C35** | **C36** |
|---|---|---|---|---|---|---|
| **Supplier 1** | 0,94 | 0,78 | 0,94 | 0,81 | 0,80 | 0,36 |
| **Supplier 2** | 0,95 | 0,84 | 0,88 | 0,83 | 0,76 | 0,57 |
| **Supplier 3** | 0,97 | 0,87 | 0,94 | 0,90 | 0,89 | 0,65 |
| **Supplier 4** | 0,99 | 0,92 | 0,97 | 0,94 | 0,91 | 0,82 |
| **Supplier 5** | 0,96 | 0,88 | 0,86 | 0,48 | 0,25 | 0,16 |
| **Supplier 6** | 0,85 | 0,88 | 0,91 | 0,93 | 0,75 | 0,64 |
| **Supplier 7** | 0,98 | 0,88 | 0,80 | 0,87 | 0,70 | 0,57 |
| **Supplier 8** | 0,95 | 0,61 | 0,90 | 0,85 | 0,41 | 0,33 |

***Table 6****: Numerical E-FCM outcomes for supplier selection problem.*

| W | **C5** | **C7** | **C22** | **C29** | **C35** | **C36** |
|---|---|---|---|---|---|---|
| **Supplier 1** | 0,13 | 0,14 | **0,15** | 0,14 | 0,20 | 0,15 |
| **Supplier 2** | 0,13 | 0,15 | 0,14 | 0,15 | 0,19 | 0,24 |
| **Supplier 3** | 0,13 | **0,16** | 0,14 | 0,16 | **0,22** | 0,27 |
| **Supplier 4** | 0,14 | **0,16** | **0,15** | **0,17** | **0,22** | **0,34** |
| **Supplier 5** | 0,13 | **0,16** | 0,13 | 0,09 | 0,06 | 0,07 |
| **Supplier 6** | 0,12 | **0,16** | 0,14 | **0,17** | 0,18 | 0,27 |
| **Supplier 7** | **0,14** | **0,16** | 0,12 | 0,16 | 0,17 | 0,24 |
| **Supplier 8** | 0,13 | 0,11 | 0,14 | 0,15 | 0,10 | 0,14 |

***Table 7****: Normalised evaluation matrix, considering the same relevance for each criterion.*

The normalised matrix highlights the fact that it is impossible to identify the best supplier only considering the output values, as the positive (in bold) and negative (underlined) values are not linked to a unique supplier, but are distributed over all the evaluated suppliers.

| | C5 | C7 | C22 | C29 | C35 | C36 |
|---|---|---|---|---|---|---|
| **V-** | 0,12 | 0,11 | 0,12 | 0,09 | 0,06 | 0,07 |
| **V+** | 0,14 | 0,16 | 0,15 | 0,17 | 0,22 | 0,34 |

***Table 8***: *Positive ideal solution and negative ideal solution.*

As this study also aims to provide an indicator for the suitability of a supplier to the company requirements, **Table 9** displays the positive ideal solution and negative ideal solution according to the company expectations: "STRONG" and "VERY STRONG" as a minimum and maximum values, respectively.

| | C5 | C7 | C22 | C29 | C35 | C36 |
|---|---|---|---|---|---|---|
| **V-** | 0,10 | 0,13 | 0,12 | 0,13 | 0,18 | 0,31 |
| **V+** | 0,14 | 0,18 | 0,15 | 0,18 | 0,24 | 0,42 |

***Table 9***: *Positive ideal solution and negative ideal solution according to company expectations.*

**Table 10** summarises the closeness indicator calculation referring to the supplier and company points of view, respectively. The final supplier ranking is displayed in **Table 11**.

| | Supplier | | | Company | | |
|---|---|---|---|---|---|---|
| | $d_i^-$ | $d_i^+$ | $CL_i$ | $d_i^-$ | $d_i^+$ | $CL_i$ |
| **Supplier 1** | 0,03 | 0,04 | 0,44 | 0,03 | 0,08 | 0,27 |
| **Supplier 2** | 0,05 | 0,01 | 0,79 | 0,01 | 0,04 | 0,16 |
| **Supplier 3** | 0,07 | 0,01 | 0,93 | 0,01 | 0,02 | 0,20 |
| **Supplier 4** | 0,11 | 0,00 | 1,00 | 0,01 | 0,01 | 0,49 |
| **Supplier 5** | 0,00 | 0,11 | 0,02 | 0,08 | 0,17 | 0,32 |
| **Supplier 6** | 0,06 | 0,01 | 0,90 | 0,00 | 0,03 | 0,14 |
| **Supplier 7** | 0,05 | 0,01 | 0,78 | 0,01 | 0,04 | 0,17 |
| **Supplier 8** | 0,01 | 0,06 | 0,16 | 0,04 | 0,10 | 0,28 |

***Table 10***: *Closeness index considering two different situations.*

| Point of view | Supplier 1 | Supplier 2 | Supplier 3 | Supplier 4 | Supplier 5 | Supplier 6 | Supplier 7 | Supplier 8 |
|---|---|---|---|---|---|---|---|---|
| Supplier | 6 | 4 | 2 | **1** | 8 | 3 | 5 | 7 |
| Company | 4 | 7 | 5 | **1** | 2 | 8 | 6 | 3 |

***Table 11***: *Supplier ranking according to different points of view.*

Considering that a higher closeness indicator (next to 1) means increased supplier suitability, suppliers 1, 5 and 8 are least suitable for the company (according to the supplier point of view). According to the company's point of view, all of the suppliers are unsuitable (too distant from company expectations), which suggests that the company needs to identify new suppliers for cooperation. This consideration is graphically described in **Figure 7.**

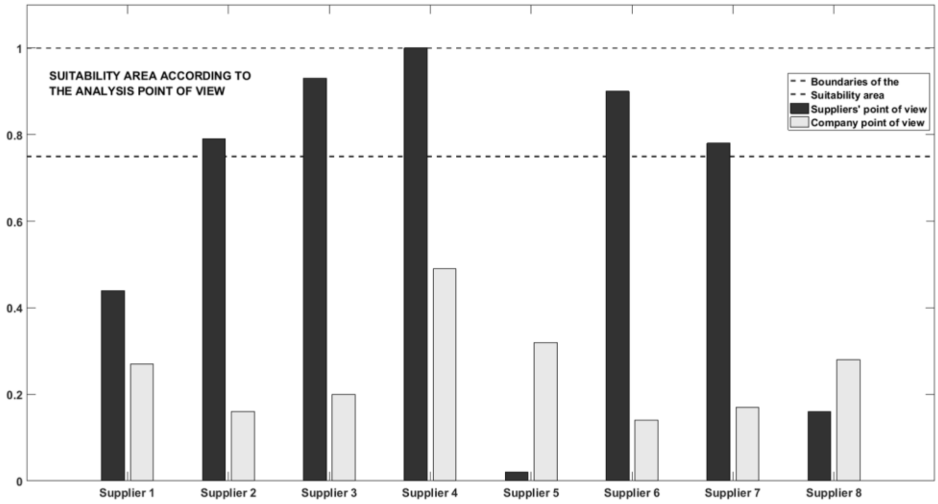


***Figure 7****: Closeness indicator evaluation*

By analyzing **Table 11**, it is possible to highlight that supplier 4 is the most suitable considering both points of view. However, comparing the relative CL values in **Table 10**, the difference among them becomes clear. Indeed, according to the standard TOPSIS procedure, the closeness value is equal to 1, while according to the company point of view, its value is equal to 0.49, approximately 51% less than the first one. Conversely, supplier 5 is the least suitable considering the supplier point of view (CL = 0.02), but it is the second most suitable supplier from the company point of view (CL = 0.32). By analyzing **Table 10**, it is evident that, from the supplier point of view, supplier 4 can be considered as the positive ideal solution ($d_4^+=0$), being very distant from the negative ideal solution ($d_4^-=0.11$), while supplier 5 can be considered as the negative ideal solution ($d_5^-=0$). However, referring to the company expectations, supplier 4 is equally distant from both the ideal solutions ($d_4^- = d_4^+=0.01$), while supplier 5 is the most distant from the negative ideal solution ($d_5^-=0.08$).

By analyzing both the ideal solutions, as indicated in **Tables 8 and 9**, it can be demonstrated that the ideal solutions are quite similar concerning the concepts "Cost performance" (C5), "Delivery performance" (C7) and "Quality performance" (C22). Furthermore, they are very different considering the concepts "Organisational performance" (C29), "Service performance" (C35) and "Flexibility" (C36). Thus, comparing the normalized E-FCM outcomes (input matrix for the TOPSIS procedure: see **Table 7**) to the ideal solutions, all of the suppliers exhibit high values in terms of cost, delivery, and quality performance. Therefore, they can be considered suitable for both points of view. The real difference among them lies in their flexibility, and organizational and service performance, in respect of which the ideal solutions are highly dissimilar.

## 6. Conclusion

In this study, E-FCMs and TOPSIS were jointly used to create a decision-making support system, in order to evaluate the logical connections among all factors involved in the supplier selection process and define a tool for supplier suitability ranking. The study incorporates different information types in a unique analysis, while also considering the presence of nonlinear relationships among certain concepts. Furthermore, this support system was tested on a supplier selection case of Italian shoes and accessories company. The outcomes of the study highlight the possibility of defining supplier ranking as a function of the considered concepts. The positive and negative ideal solutions were defined considering not only the standard TOPSIS procedure but also company expectations. Considering the standard TOPSIS ideal solutions, the majority of suppliers are found to be highly suitable for the company. In contrast, if the ideal solutions are defined considering the company's point of view, all of the suppliers are found to be unsuitable for cooperation with the company, to the extent that it is suggested that the company select different suppliers. As these two results are considerably different, a means of addressing this would be to consider the concepts related to the company expectations in the E-FCM. In this manner, they would have an impact on the map outcomes and supplier judgment. The proposed tool allows for evaluating a single supplier to define its suitability, but can also be used to assess the entire procurement system. Finally, it responds to the company's need for an unambiguous and inexpensive tool that can efficiently direct the economic, instrumental, and human resources intended for procurement operations.

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## APPENDIX A

### *A.1 The hidden paths identification function*

Once defined the FCM adjacent matrix, it is possible to highlight all of the hidden paths from each concept ending in the top-event one that represents the target for the analyzed issue. The final result is the variable hidden_paths explaining all the FCM hidden paths.

```
function hidden_paths=PathsIdentification(adjacent_matrix,top_event)

% Begin: all the one-to-one connections are identified
[r c v]=find(a~=0);
arches=[r c];
[val ind]=sort(arches(:,1));
arches=arches(ind,:);
% end
% System output initialisation
hidden_paths=[];

% all paths starting from each node are analysed
for node=1:size(adjacent_matrix,1)-1
    AMapp=adjacent_matrix;
    [r c v]=find(AMapp~=0);
    OneStepNode=[r c];

    % Condition 1: All the paths starting from the top event node are omitted
    % Begin Condition 1
    [r c v]=find(OneStepNode(:,1)==top_event);
    OneStepNode(r,:)=[];
    % end Condition 1

    paths=OneStepNode(OneStepNode(:,1)==node,:);
    n=size(paths,1);
```

```
    [r c v]=find(paths(:,end)~=0);

    % Condition 2: all of the one-step nodes not ending in the top_event one are
valued
    % Begin Condition 2
    [r c v]=find(paths(r,end)~=top_event);
    % end Condition 3

    % Condition 3: it is prevented the possibility to identify more times the same
path
    % (relevant in case of cycles identification)
    % Begin Condition 3
    AMapp(node,:)=0;
    AMapp(:,node)=0;
    % end Condition 3

    paths1=[];
    while not(isempty(r)) % the procedure is applied until one-step node are
identified
        for j=1:size(paths,1)
            [r1 c1 v1]=find(AMapp~=0);
            OneStepNode=[r1 c1];

            % Begin Condition 1
            [r2 c2 v2]=find(OneStepNode(:,1)==top_event);
            OneStepNode(r2,:)=[];
            % end Condition 1

            EndNode=paths(j,end);
            if EndNode~=0 && EndNode~=top_event
                [r3 c3 v3]=find(OneStepNode(:,1)==EndNode);
                replications=length(r3);
                app=[repmat(paths(j,:),replications,1) OneStepNode(r3,2)];
                [r4 c4 v4]=find(arches(:,1)==EndNode);
                if not(isempty(r4))
                    AMapp(EndNode,arches(r4,2))=0;
                end
            else
                app=[paths(j,:) 0];
            end
            paths1=[paths1;app];
         end
        paths=paths1;
        paths1=[];
        [r c v]=find(paths(:,end)~=0);
```

```
        % begin Condition 2
        [r c v]=find(paths(r,end)~=top_event);
        % end Condition 2
    End
       % The previous iteration paths are concatenated to the new ones
       hidden_paths=concatenation([hidden_paths;paths]);
end
```

*A2. Indirect and Total Effects calculation function*

The following matlab code allows us to implement equations 5 – 6, taking as input variables the weighted FCM matrix and the hidden paths matrix. As outputs, IndirectEffects and Total Effects contains the IE and TE for each concept. The MainPaths variable contains the most relevant hidden paths with higher TE value.

```
function [IndirectEffects TotalEffects MainPaths]=
IndirectTotalEffectCalculation(weighted_matrix, hidden_paths)

% Output varibales inizialisation
IndirectEffects=[];
TotalEffects=[];
MainPaths=[];

% All the identified hidden paths are analysed
for i=min(hidden_paths (:,1)):max(hidden_paths (:,1))
    [r c v]=find(hidden_paths(:,1)==i); % all paths starting from node i are
identified
    if not(isempty(r))
        PathsToAnalyse= hidden_paths(r,:);
        effetti=[];
        for j=1:size(PathsToAnalyse,1)
            app= PathsToAnalyse (j,:);
            app(app==0)=[];
            app1=[];
            for t=1:length(app)-1
                app1=[app1 weighted_matrix(app(t),app(t+1))];
            end
            app2=abs(app1);
            [valore index]=min(app2);
            effects =[effects; app1(index)];
        end
        IndirectEffects=[IndirectEffects;effetti];
```

```
        app1=abs(effects);
        [value index]=max(app1);
        TotalEffects=[TotalEffects; [i effects (index)]];
        [r c v]=find(effects == effects (index));
        if length(r)>1
            MainPaths=concatena( MainPaths, [PathsToAnalyse (r,:) effects (r)]);
        else
            MainPaths=concatena( MainPaths, [PathsToAnalyse (index,:) effects
(index)]);
        end
     end
 end
```

*A3. The FCM simulation function*

Once defined all the scenarios to be analyzed and described in the input variable "input", using the FCMsimulation function, it is possible to analyze the system status. For the proposed study, the hyperbolic tangent function has been chosen with lambda equal to 1.

```
function SimulationResults=
FCMsimulation(weighted_matrix,input,TypeThresholdFun,lambda,Threshold,MaxIt)

Cold=input;
iter=1;
SimulationResults =Cold; % Cold is the simulation result at the previous iteration
while not(sum(abs(Cnew-Cold)<= Threshold)==size(FCM,1)  || iter>MaxIt)
    Cnew=(input+Cold)*FCM;
    for j=1:length(Cnew)
        switch TypeThresholdFun
            case -1 % hyperbolic tangent function
                Cnew(j)=(exp(lambda*Cnew(j))-exp(-
lambda*Cnew(j)))/(exp(lambda*Cnew(j))+exp(-lambda*Cnew(j)));
            case 1 % sigmoid function
                Cnew(j)=1/(1+exp(-lambda*Cnew(j)));
        end
    end
    SimulationResults =[SimulationResults;Cnew];
    iter=iter+1;
    Cold=Cnew;
End
```

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