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AN INTEGRATED FUZZY ANP-MOP APPROACH FOR PARTNER SELECTION PROBLEM AND ORDER ALLOCATION OPTIMIZATION: THE CASE OF VIRTUAL ENTERPRISE CONFIGURATION

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Abstract. Virtual networked enterprises have become a necessity for organizations to integrate better with the highly competitive markets in the 21st century. Virtual Enterprise (VE) depends on the performance of its members. Hence, the development of an effective methodology for the evaluation and selection of the suitable partners is a crucial issue toward forming a successful VE. The aim of this paper is to address the partner selection problem and order allocation optimization for the VE creation from Virtual organizations Breeding Environments (VBE) to respond to a specific Business Opportunity (BO). In this context, an exhaustive list of evaluation criteria is identified. A two-stage methodic approach is also proposed to make an objective evaluation for selecting the suitable partners of a VE with considering the BO requirements. In the first stage, a fuzzy analytical network process is used to determine the weights of the partner evaluation criteria. In the second stage, the obtained criteria weights are incorporated into a multi-objective programming model, which is solved using Weighted Sum Method to identify the appropriate VE configuration. Two illustrative examples artificially designed as well as a real case study from a network in textile sector are presented to demonstrate the effectiveness of the developed approach.

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1. Introduction

Nowadays, organizations, especially the Small and Medium sized Enterprises (SME) seek to explore new organizational models to succeed in dynamic market. The concept of Collaborative Networks (CNs) is considered as the most promising business strategies for enterprises to face global competition. Among the large variety of CNs forms, the Virtual Organizations Breeding Environment (VBE) is characterized by long-term strategic alliances of enterprises. The integration into a VBE increases the chance and the preparedness of enterprises towards rapid configuration of temporary alliances for collaboration. In fact, when faced to a Business Opportunity (BO), a subset of organizations should be selected from VBE members in order to form a Virtual Enterprise

Keywords. Virtual Enterprise, partner selection, order allocation, Fuzzy ANP, multi-objective programming.

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(VE). The VE is a tactical combination of core resources and competencies of independent organizations. It is a temporary dynamic alliances tailored to respond to a unique BO [1,2].

The life cycle of a VE includes four phases: formation, design, operation and dissolution. The most important phase is the VE formation since the success of a VE consortium is strongly dependent on chosen partners. Therefore, Partner Selection (PS) is a fundamental and key issue in the VE configuration. In this respect, the present paper aims to provide a decision support approach to address the PS problem for VE configuration from a VBE. The developed approach consists of a combination of a Fuzzy Analytical Network Process (ANP) technique and a Multi-Objective Programming (MOP) model. The proposed approach is applied to two illustrative examples, which are artificially designed to demonstrate its effectiveness. Furthermore, a real world case from Tunisian textile industry is addressed to demonstrate the applicability of the proposed approach.

The remainder of this paper is organized as follows: Section 2 presents a discussion of the state of the art dealing with partner evaluation criteria in VE configuration context as well as the different techniques used in PS problem. Section 3 presents the description and the formulation of the problem. Section 4 presents the developed approach for VE partner selection and order allocation optimization. Section 5 illustrates and discusses the results of the developed approach using two illustrative examples and a real case study. Finally, Section 6 draws the conclusions and proposes opportunities for future studies.

2. Literature review

The PS problem requires consideration of evaluation criteria, which are different from one study to another. For instance, to address the PS problem for VEs creation, Nikghadam *et al.* [3] used four main criteria: price, on-time delivery reliability, enterprises' past performance and service quality. In the Xiao *et al.*'s study [4], the PS decision is made based on five main criteria including cost, risk, time, trust and quality. Mladineo *et al.* [5] considered price, time, quality and transportation cost as the most important criteria to select the optimal partners of a VE. Igor *et al.* [6] evaluated partners using competencies, price, delivery time, geographical closeness, payment terms, delivery terms, index of partner skills, index of quality, realization time and reply for quotation. Dong and Wan [7] evaluated the partners based on five main criteria, which are risk, time, cost, reputation and quality in order to design a new VE for a specific business. Some authors explored the PS problem in the context of VE configuration from sustainability perspective. For instance, Andres *et al.* [8] used trust assessment, strategies alignment and value systems alignment for partner evaluation to create a stable and sustainable VE.

An analysis of literature reveals that there is a convergence of several authors toward common factors, namely cost, quality and delivery. We note also that some of researchers neglect the decision level in the definition of the PS criteria for the aim of VE configuration. In fact, identifying the suitable partners of a VE is considered as a tactical decision. However, the reputation, past performance and trust criteria are considered by Partanen and Möller [9] as strategic assets for partners. In addition, sustainability related criteria should be considered in the design of VBE and not VE since they represent strategic concepts. This is confirmed by Camarinha-Matos *et al.* [10] who consider that the VBE can facilitate the interactions and the engagement of the network members needed in any efforts toward sustainability. This study proposes a decision framework comprising the most important tactical PS criteria to create the best VE from a VBE for a specific BO.

To cope with PS problem, several approaches are used in both individual and integrated ways. Multi Criteria Decision Making (MCDM) approaches are recognized for their advantages in dealing with multiple selection criteria. These approaches have a methodological framework that aims to provide Decision Makers (DMs) with a knowledgeable recommendation from a set of alternatives, which are evaluated based on multiple criteria. This process becomes complex if imprecise and uncertain data are used in the assessment process. Therefore, it is better to make the evaluation problem under fuzzy conditions. For instance, Kara *et al.* [11] proposed a Fuzzy Analytical Hierarchical Process (FAHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to respectively, determine the considered criteria weights and to rank the different alternatives corresponding to the alternative partnerships. Büyüközkan and Güleryüz [12] applied the same hybridization but making both approaches under fuzzy conditions. Uygun *et al.* [13] implemented an integrated DEMATEL and Fuzzy ANP techniques to address an evaluation and PS problem.

The other research stream uses mathematical models for partner evaluation and selection. Xiao *et al.* [4] and Mladineo *et al.* [5] formulated the PS as a multi-objective optimization problem with constraints. Considered selection criteria are expressed in terms of mathematical objective functions. Additionally, there is a number of studies, which integrated the Multi Criteria Decision Making (MCDM) approaches with mathematical models. Wu *et al.* [14] implemented an integrated approach based on ANP and a MOP. Nikghadam *et al.* [3] combined the FAHP with a Goal Programming (GP) model. The FAHP is used to determine customer preferences for main criteria. The GP model aims to solve the VE partner selection problem. In their study, they provided a comprehensive and thorough literature review on published PS methods in VE creation. They concluded that integrated Fuzzy AHP approaches have the most citations.

Actually, mathematical programming models seems to be the appropriate decision tool as it allows the DMs to explicitly formulate the objective functions and then make an objective decision. In addition, it only consider quantitative criteria when the consideration of the qualitative factors may cause a significant problem in the evaluation process. Furthermore, in most cases, the selection criteria are often conflicting and thus require an analysis of the trade-offs among them. Mathematical models can face to this problem in order to make an efficient PS decision as well as it can optimize the order allocation problem. However, it cannot consider the interdependences and interactions among the various criteria. Additionally, in the context of VE creation from a VBE for a given BO, it is necessary to weighting the multiple objectives (or criteria) because its importance level differ from one BO to another. MCDM approaches, notably the ANP technique, can overcome these two shortcomings. However, the ANP cannot optimize the order allocation among partners. Therefore, the combination of a MOP model and ANP technique guarantee the effectiveness of solving the PS and the order allocation problems. Nevertheless, it is better to make the ANP technique application under fuzzy conditions in order to face the subjectivity and the vagueness of DMs judgments. Hence, an integrated (Fuzzy ANP-MOP) approach is implemented in this study.

3. Description of the problem and proposed methodology

When a BO is identified by a VBE member or by a VBE broker, a VE should be created from the members' pool, as shown in Figure 1. This study focuses on an objective evaluation of the VBE entities based on tactical criteria to select the suitable partners of VE and optimize the order allocation. The VBE broker is responsible for the VE configuration process. This entity is then referred to as a DM.

The VBE is assumed to be composed from a set of potential organizations having a horizontal collaborative relationship where their competences and their activities are close. Each member is distinguished from the others with particular technical competencies in the field of a given activity. The entities are strategically selected from the open universe in order to guarantee their quick adaptation to respond to market opportunities. They are assumed to be geographically located in the same region.

The proposed methodology consists of two stages. The first stage covers the assessment process. The main tactical evaluation criteria and its corresponding sub-criteria are identified. The interactions among them are also

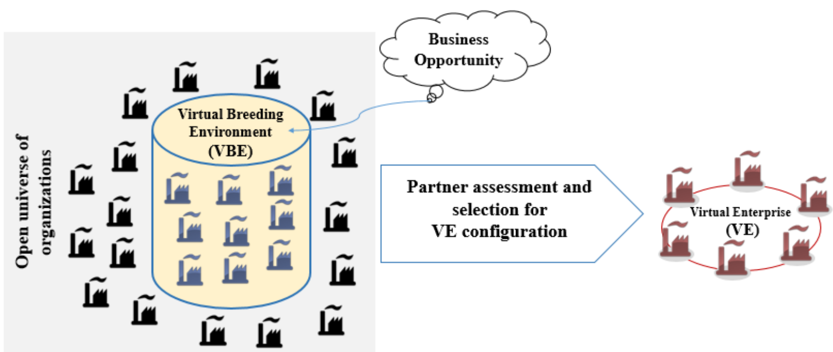

Figure 1. Problem statement.

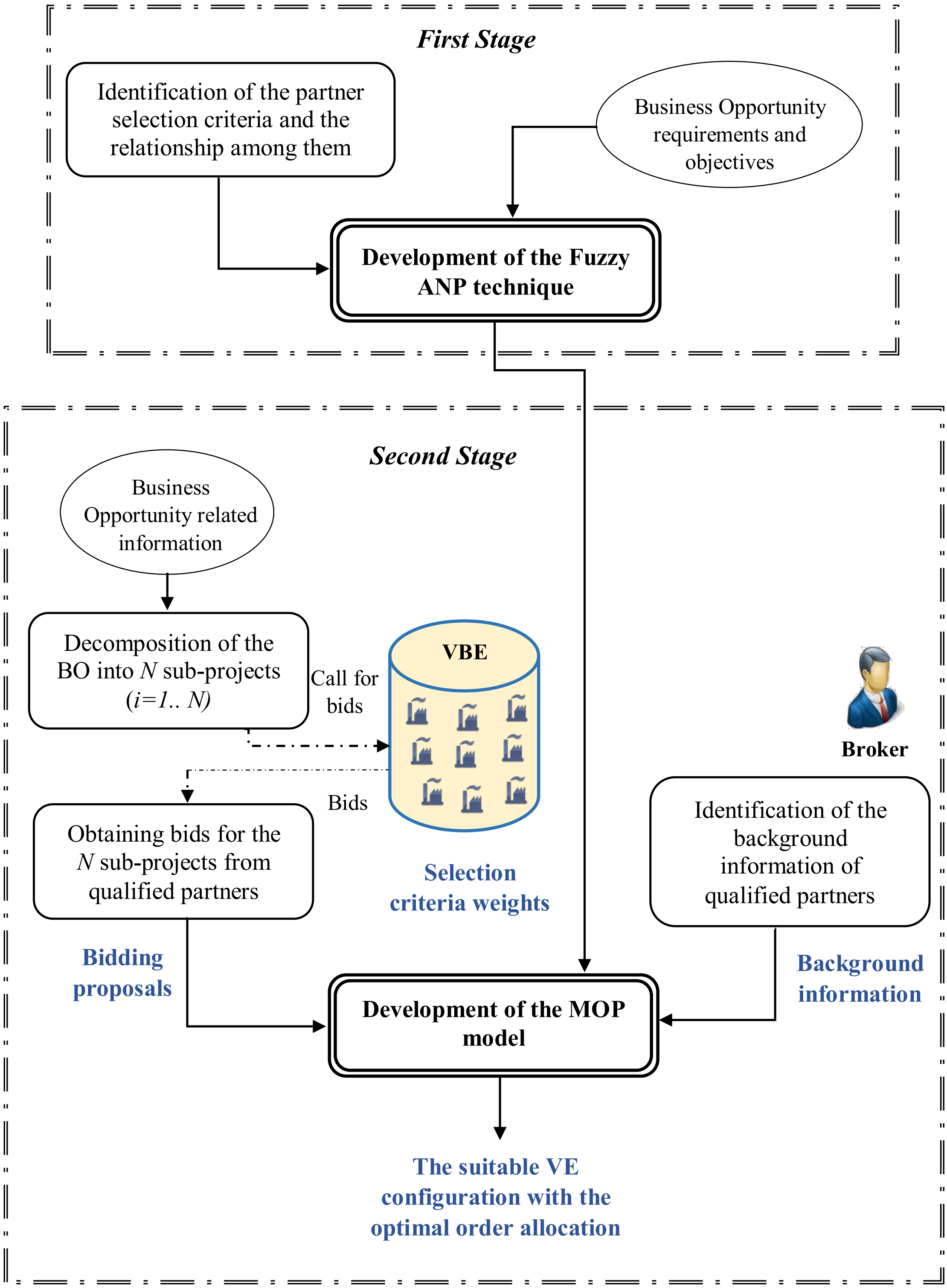

Figure 2. Proposed approach for the VE conguration.

identified in order to develop the decision hierarchy structure for the assessment. Then, a Fuzzy ANP technique is applied and the DM judgments on pairwise comparisons are assigned according to the BO objectives and requirements. The results of the first stage are the selection criteria weights. The second stage aims to achieve the PS and order allocation decisions. In fact, the BO is divided into N sub-projects $(i = 1, 2, \ldots, N)$. Then, for each sub-project i, the qualified VBE members submit bids. Based on partners' bids and background information provided by broker, a MOP model is developed with respect to the weights of the evaluation criteria obtained in the first stage. The suitable partner for each sub-project is then selected. Finally, the appropriate VE configuration as well as the optimal order allocation are obtained to achieve the BO.

4. The proposed Fuzzy ANP-MOP approach

The different steps of the proposed approach are presented in Figure 2.

4.1. First stage: Identification of partner selection criteria weights

4.1.1. Definition of selection criteria

Identifying the relevant PS criteria is essential priori to develop any partnerships. For the purpose of this paper, tactical criteria should be considered seeing that the VE is a tactical combination of core competencies from the strategic long-term VBE. Tactical criteria must reflect the performance and competitive priorities of the VBE members in order to choose the best group of firms who can achieve customer satisfaction. Four main performance measures are considered as being the most important, namely cost, quality, delivery and flexibility. Each criterion is represented with two sub-criteria. The definition of each sub-criteria is shown in Table 1.

Interdependences and interactions between criteria can exists. In fact, a criterion is related to another criterion when at least one of its sub-criteria depends on at least one sub-criteria of another one. Based on the considered selection criteria and on the outer-dependence relationships between them, the ANP network structure is build, as shown in Figure 3.

Table 1. Tactical partner selection criteria.

Main criteria	Sub-criteria	Description
Cost		The inclusion of performing cost of an activity as well as the transportation cost.
Quality	Quality level	The conformance of the product quality to the quality specifications required by customer.
	Service level	The capability of partner toward four constructs: availability, responsiveness, reliability and respect of contract conditions.
Delivery	On-time delivery	The ability of partner to deliver a product. or a service on time and in full.
	Lead time	The time spent on order processing, completion of the activity and transportation.
Flexibility	Flexibility level	The system's ability to accommodate and react to the possible fluctuations in terms of processes, operations, programs and materials.
	Establishment flexibility	The ease with which relationships can be built with new partners by measuring the expenses occurred during the building of relationships such as personal contacts, the transaction fee and information system connection.

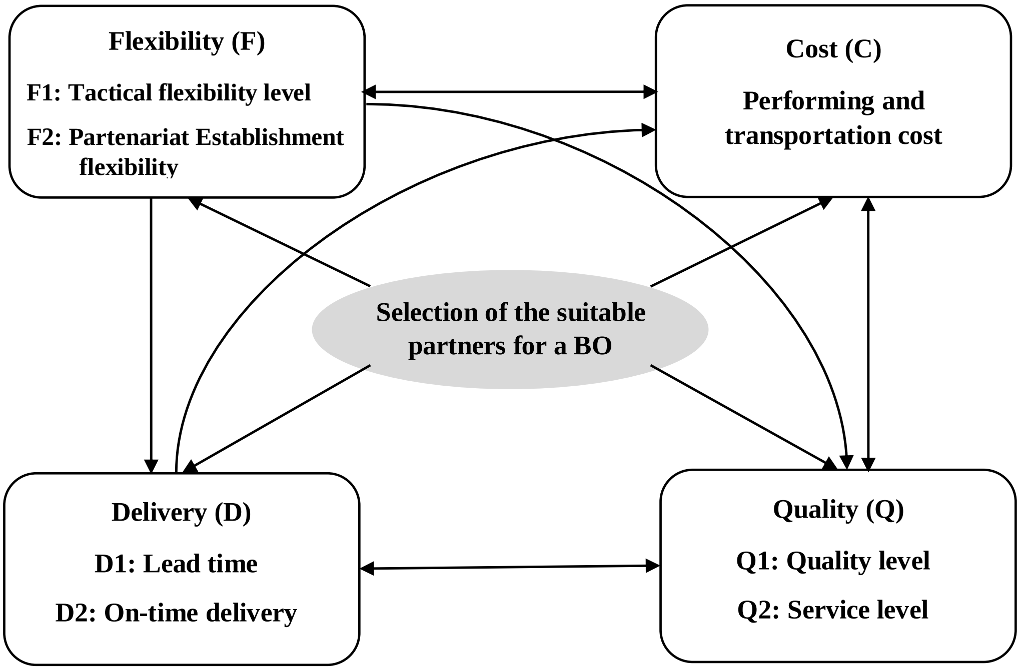

FIGURE 3. The ANP network structure.

4.1.2. Development of the Fuzzy ANP technique

Without consideration of relationship between criteria, series of pairwise comparisons are formed to determine the local weights of main criteria and sub-criteria. These pairwise comparisons are designed using linguistic terms, which are useful in complex situation to express the human judgments in conventional quantitative expressions. The judgments are then converted to Triangular Fuzzy Numbers (TFN) on the basis of Saaty's 1–9 scales [15]. To handle the fuzzy comparison matrices, a Fuzzy Preference Programming is applied following its non-linear form. The consistency of each comparison is checked in order to control the quality of given priorities. In the next step, the relationships between criteria is considered. Series of pairwise comparisons are formed to determine the relative importance of all sub-criteria against each other. These pairwise comparisons are treated by the manner described above. An unweighted super-matrix is then formed by blocks representing matrices resulted from pairwise comparisons of sub-criteria. A cluster matrix is also provided to determine the relative dependence between main criteria. Then, the unweighted super-matrix is multiplied by the cluster matrix in order to make the sum of each super-matrix column equal to unity. The result is a weighted super-matrix, which gives the global weights of sub-criteria. The weighted super-matrix is powered repeatedly until the super-matrix's row values converge to the same value for each column of the matrix. The resulted matrix is named limit super-matrix. Finally, the weights of partner evaluation sub-criteria can be obtained.

4.2. Second stage: Development of a MOP model for partner selection and order allocation

As shown in Figure 2, the VBE members submit a set of bids to accomplish the BO sub-projects. As mentioned above, the short-term objectives of the network are to ensure the satisfaction of customer requirements in terms of cost, quality, delivery and flexibility. The problem is formulated as a multi-objective mathematical model.

The assumptions, notations and formulation of the MOP model are presented as follow:

Assumptions

- The N independent sub-projects of the BO can be performed in parallel.
- Each sub-project have a deterministic demand.
- A sub-project can be performed by only one partner.
- The partners' capacities are fixed according to their availability.
- Lead time of the sub-project allocated is deterministic and fixed by the partner. It includes order processing, execution and transportation times.
- Shortage of planed quantity, loss and damage during delivery are not allowed.
- The proposal of a partner for a sub-project completion includes the following information:
  - ✓ Performing cost
  - ✓ Transportation cost
  - ✓ Establishing partnership cost
  - ✓ Capacity
  - ✓ Lead time

Notations

p: Index of partner
i: Index of sub-project
P: Number of the VBE members
N: Number of sub-projects of the BO
$F(i)$: The set of qualified partners for performing the sub-project i

Parameters

C_{ip}: Performing cost of sub-project i by partner p
CT_{ip}: Transportation cost of sub-project i by partner p
D_i: Demand of sub-project i.
B: Budget allocated to the BO
DD: Deadline of the BO required by customer
Cap_{ip}: Capacity of partner p for performing sub-project i
lt_{ip}: Lead time to deliver the sub-project i from partner p
f_{ip}: Quality level of sub-project i from partner p
s_{ip}: Service level of sub-project i offered by partner p
LL_p: On-time delivery of partner p
E_p: Cost for establishing partnership with partner p
FL_{ip}: Tactical flexibility level of partner p by performing sub-project i

Decision variables

y_{ip}: Binary variable indicating whether partner p is selected for performing sub-project i

Objective functions

$$\mathrm{Min}\, Z_1 = \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot (C_{ip} + \mathrm{CT}_{ip}) \tag{4.1}$$

$$\mathrm{Max}\, Z_2 = \frac{1}{N} \cdot \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot f_{ip} \tag{4.2}$$

$$\mathrm{Max}\, Z_3 = \frac{1}{N} \cdot \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot s_{ip} \tag{4.3}$$

$$\text{Min } Z_4 = \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot lt_{ip} \tag{4.4}$$

$$\text{Max } Z_5 = \frac{1}{N} \cdot \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot \text{LL}_p \tag{4.5}$$

$$\text{Min } Z_6 = \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot E_p \tag{4.6}$$

$$\text{Max } Z_7 = \frac{1}{N} \sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} \cdot \text{FL}_{ip} \tag{4.7}$$

Constraints

$$\text{Cap}_{ip} \geq y_{ip} \cdot D_i \qquad \forall i, p \tag{4.8}$$

$$\max_p (lt_{ip} \cdot y_{ip}) \leq \text{DD} \qquad \forall i \tag{4.9}$$

$$\sum_{i=1}^{N} \sum_{p}^{F(i)} [y_{ip} \cdot (C_{ip} + \text{CT}_{ip}) + E_p . y_{ip}] \leq B \tag{4.10}$$

$$\sum_{p}^{F(i)} y_{ip} = 1 \quad \forall i \tag{4.11}$$

$$\sum_{i=1}^{N} \sum_{p}^{F(i)} y_{ip} = N \tag{4.12}$$

$$y_{ip} \in \{0, 1\} \quad \forall i, p \tag{4.13}$$

In the above formulation, equations (4.1)–(4.7) show the objective functions. Equation (4.1) aims to minimize the total cost including, respectively, performing and transportation costs. The performing cost is processing fee, which a partner provides to finish the assigned sub-project. The transportation cost is the transport expenses. Equation (4.2) maximizes the average quality level of the selected partners in order to meet the quality specifications required by the customer. In fact, the total quality is divided with number of sub-projects to get average value of quality of the optimal VE obtained. Equation (4.3) aims to maximize the average service level of the selected partners. Equations (4.4) and (4.5) consist of minimizing the total lead time of the sub-projects and maximizing the average on-time delivery. Equation (4.6) aims to minimize the total establishment cost which includes all of the expenses occurred during the build of relationship with a partner such as information system connection (e.g. EDI, CRM). Equation (4.7) aims to maximize the average flexibility level in order to meet dynamic changing customers' expectations and market opportunities. The constraints of the problem are represented in equations (4.8)–(4.13). Equation (4.8) stipulates that the selected partner should have the sufficient capacity to satisfy the demand. Equation (4.9) ensures that the BO sub-projects should be completed no later than the required deadline. Equation (4.10) stipulates that the total cost cannot be larger than the global BO budget. Equation (4.11) ensures that only one partner can be assigned to each sub-project. Equation (4.12) guarantees that all sub-projects are implemented. Equation (4.13) specifies the domain of the decision variable.

The model parameters are partners' scores for eight sub-criteria: cost, quality level, service level, on-time delivery, lead time, flexibility level and establishment flexibility. These scores are calculated according to its corresponding significations. The costs values of processing, transport and establishment flexibility (C_{ip}, CT_{ip} and E_p, respectively) as well as the lead time delivery (lt) are collected during the bidding phase. The values of other criteria, which are quality level, service level, on-time delivery and flexibility level, are calculated based on information recorded in a database. This database gathers the partners' performances of previous projects and it is updated whenever a partner is selected for performing a BO. The calculation method of each criteria is described below.

The calculation of quality level and on-time delivery score is inspired from the proposition of Nikghadam *et al.*'s study [3]. In fact, Nikghadam *et al.* used these two criteria to measure the partners' past performance to select the appropriate members of a VE. The quality level (f_{ip}) is expressed in terms of percentages of sub-projects compliance of customer's requirements as shown in equation (4.14).

$$f_{ip} = \frac{\mathrm{CS}_{ip}}{\mathrm{TS}_{ip}} * 100 \tag{4.14}$$

where CP_{ip} is the number of compliant sub-projects performed by partner p

TS_{ip} is the total number of sub-projects i allocated to partner p

The on-time delivery (LL_p) score is expressed in terms of percentages of partner's capability to deliver on time and in full, of the previous participation on short-term collaborations. In fact, this criterion depends on the quantity delivered on time as well as on delay duration in the completion of a sub-project. It is calculated using equations (4.15)–(4.17).

$$\mathrm{LL}_p = 100 - r_p e^{l_p} \tag{4.15}$$

where

$$r_p = \frac{\mathrm{LS}_p}{\mathrm{TS}_p} * 100 \tag{4.16}$$

$$r_p = \frac{\mathrm{DL}}{\mathrm{TD}} * 100 \tag{4.17}$$

LS_p is the number of late delivered sub-projects

TS_p is the total number of sub-projects performed by partner p

DL is the delay duration

TD is the total delivery time.

The term $r_p e^{l_p}$, in equation (4.15), expresses the penalty function of late delivery as an exponential function. In fact, the penalty increases exponentially as the length of delay increases [3].

According to Narain [16], the flexibility elements in tactical level are material flexibility, operations flexibility, process flexibility and program flexibility. In this study, the partner's flexibility level is a sum weighted of these four elements. In fact, material flexibility consists of the capability to make products with different composition and dimensions of raw materials. Operations flexibility is defined as the ability to manufacture a product in different ways with different process plans by either an exchange or a substitution of certain operations by others. Process flexibility is the ability of a manufacturing system to produce a set of product types without major set-ups. Program flexibility is the system's ability to run virtually untended for a long period. The signification of each of flexibility sub-criteria can be adapted with respect to considered manufacturing process.

The flexibility level (FL_{ip}) is calculated using equation (4.18).

$$\mathrm{FL}_{ip} = \left(\sum_{k=1}^{4} W_k \frac{a_{ipk}}{3} \right) * 100 \tag{4.18}$$

where W_k is the weight of flexibility element k.

a_{ipk} is the level of the flexibility element k attributed to partner p toward sub-project i.

W_k values are fixed by the broker according to the business requirements in a way that its sum is equal to unity. In addition, for each set {sub-project, partner, flexibility element}, the broker attributes a flexibility level

(a_{ipk}) to partners based on previous projects. This level varies between 1 and 3, as follows:
$a_{ipk} = 1$ if a partner has a low flexibility;
$a_{ipk} = 2$ if a partner has a medium flexibility;
$a_{ipk} = 3$ if a partner has an important flexibility.

The partner's service level (s_{ip}) is also a sum weighted of four elements, which are availability, responsiveness, reliability and respect of contract conditions. It is calculated using equation (4.19). X_k values are fixed by the broker according to the business requirements. The level to be attributed to partners toward each of considered elements (b_{ipk}) is based on previous projects. This level varies between 1 and 3.

$$s_{ip} = \left(\sum_{k=1}^{4} X_k \frac{b_{ipk}}{3}\right) * 100 \tag{4.19}$$

where X_k is the weight of element k of the service level criteria.
b_{ipk} is the level of element k of the service level criteria attributed to partner p toward sub-project i.

4.3. Resolution method of MOP model

Several resolution methods have been developed for Multi-Objective Optimization (MOO) problems. The classification of these methods vary significantly. Drawing on literature, two main classification exists. Firstly, according to Van Veldhuizen [17], it is possible de classify them into three categories depending on when the DM articulates his preference about the different objectives. In other words, they depends on how optimization and decision process are combined. The three methods are *a priori* preference articulation, progressive preference articulation and *a posteriori* preference articulation, in which the DM must specify his preference, before, during and after the optimization process is run, respectively. Secondly, another classification proposed by Coello [18] into two categories depending on the optimization manner of the multiple objective functions. The two methods are aggregative approaches, which combine the multiple objectives into a single optimization criterion and non-aggregative approaches, in which there is no fusion of the various objectives into one objective.

Within the framework of this research, the DM articulates his preference about the objectives according to the requirements of the BO. Indeed, the result of the first stage of the proposed approach consists of the selection criteria weights, which are formulated as objective functions to optimize the VE configuration. Therefore, the priori preference optimizations methods are the most appropriate for this study. According to Ben Yahia [19], this family is convenient with aggregative methods because the objective functions are gathered into one objective in such a way that the objective functions are parameterized by analogy to DM before search. In addition, in the *a priori* methods, it is not interesting to use the non-aggregative methods, which provides a set of efficient solutions, because the DM is looking for just one optimal solution.

There are various techniques in the frame of *a priori* preference aggregative optimization. The Weighted Sum Method (WSM), also known as scalarization, is one of the most widely used method for MOO problems due to its simplicity [20]. This method consists in multiplying the objective functions by its respective weights and then adding all of them together to obtain only one global objective function. The weighting coefficients of the weighted sum problem give the "trade-off" rate information between the objective functions. The WSM stipulates that all the objectives to be aggregated should be expressed in the same unit of measure and that the scales used for each objective should be homogeneous. Therefore, each objective is normalized.

The formulation of the WSM is as follows:

$$U\left(f_1\left(x\right), \ldots, f_M\left(x\right)\right) = \sum_{j=1}^{M} W_j \cdot C_j \cdot f_j(x) \tag{4.20}$$

$$\sum_{j=1}^{M} W_j = 1 \tag{4.21}$$

$$W_j \in [0,1] \;\; \forall\, j \tag{4.22}$$

Where U represents the aggregative objective function of the M objectives, W_j represents the weights of the M objectives assigned by the DM and C_j represents the normalization factor. Several normalization techniques exists [21]. In this paper, the objective functions are normalized by dividing each of one by its best evaluation. So, the C_j factors are defined as $\frac{1}{f_j^*(x)}$, where $f_j^*(x)$ is the optimal solution of the objective function f optimized separately. In fact, the problem is solved M times and in each time, the objective function optimizes a unique criterion. In this study, the mathematical model is solved 7 times. In each time, one of the seventh objectives represents the objective function of the model with respect to the constraints shown in equations (4.8)–(4.13). The result of each run consists of an optimal value of the objective (criterion) optimized.

Through the WSM, the MOP developed for PS problem is converted to a single objective optimization problem. By applying equation (4.20), the new obtained objective function is shown in equation (4.23), respecting the same constraints of the previous formulation shown in equations (4.8)–(4.13).

$$\mathrm{Min} Z = W_C \frac{Z_1}{Z_1^*} - W_Q \frac{Z_2}{Z_2^*} - W_S \frac{Z_3}{Z_3^*} + W_L \frac{Z_4}{Z_4^*} - W_O \frac{Z_5}{Z_5^*} + W_E \frac{Z_6}{Z_6^*} - W_F \frac{Z_7}{Z_7^*} \tag{4.23}$$

The coefficients W_C, W_Q, W_S, W_L, W_O, W_E and W_F are respectively the weights of the cost, quality level, service level, lead time, on-time delivery, establishment flexibility and flexibility level. These weights are obtained through the Fuzzy ANP technique. They should respect constraints of the equations (4.21) and (4.22). These weights are used to describe the degree of the relative importance of each objective function. The coefficients Z_1^*,Z_2^*,Z_3^*, Z_4^*, Z_5^*, $Z_6^*$and Z_7^* represents the optimal value of the seven objective functions when they are optimized separately.

5. Applications of the proposed approach

In this section, two illustrative examples and a real world case study are considered in order to explain the implementation of the developed Fuzzy ANP-MOP model and to demonstrate its applicability in practice for VE configuration.

5.1. Illustrative examples

Two illustrative examples are artificially designed. Data of the examples are manually made and inspired from the literature. In fact, the data related to the BO (budget, deadline, etc.) are inspired from Nikghadam *et al.*'s study [3], who implemented a real case study from industrial zone in Ankara for VE creation context. In addition, some of the model parameters, such as service level, quality level, on-time delivery are fixed based on the same study. The three costs are proposed based on Su *et al.*' study [22]. The flexibility level proposed in this study is an aggregation of the four tactical flexibility elements.

In these examples, it is assumed that a network of manufacturing companies involves 14 partners in the same sector with different resources and core competencies. Assume that the broker receives a BO from a customer. The required deadline of the BO is Ten Months and the budget allocated is 34 0000$. The broker initiates the configuration of a VE to meet the customer requirements and objectives. Assume that the BO consists of four independent sub-projects ($N = 4$). Each of these sub-projects is opened for bidding.

5.1.1. Example 1

In the first example, it is assumed that each partner can submit for only one sub-project. After receiving the bids for each sub-project, two enterprises are considered to be qualified for sub-project S_1 (P_1 and P_2), five for sub-project S_2 (P_3, P_4, P_5, P_6 and P_7), four for sub-project S_3 (P_8, P_9, P_{10} and P_{11}) and three for sub-project S_4 (P_{12}, P_{13} and P_{14}). Detailed information bided for each sub-project and its corresponding calculations are presented in the Tables 2–4. In fact, the demand of each sub-project is given in Table 2. The establishment cost of each partner is shown in Table 3. The processing and transport costs, the partner's capacity, the lead time, the quality level, the service level, the on-time delivery and flexibility level of each candidate are described

TABLE 2. Sub-projects demand (Illustrative Examples).

	S_1	S_2	S_3	S_4
D_i (Number of units)	300	100	200	100

TABLE 3. Establishment cost of each partner.

	P_1	P_2	P_3	P_4	P_5	P_6	P_7
E_p (10^3\$)	2.016	2.269	0.841	3.055	2.489	3.311	2.153
	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}
	1.562	0.848	2.933	2.150	5.315	6.415	5.484

TABLE 4. The processing cost, the transport cost, the partner's capacity, the lead time, the quality level, the service level, the on- time delivery and flexibility level of each partner (Example 1).

	S_1		S_2					S_3				S_4		
	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}
C_{ip} (10^3\$)	85.3	74.6	55.5	82.6	91.2	4	51.6	99.4	96.5	86.4	92.9	89.7	90.2	84.0
CT_{ip} (10^3\$)	5.3	3.1	4.1	3.7	2.6	3.8	2.0	2.8	2.5	4.2	5.5	4.9	3.6	5.7
Cap_{ip} (Number of units)	320	300	100	110	150	130	80	170	220	190	210	150	120	100
lt_{ip} (Month)	8.8	5.3	7.6	4.5	8.9	10.5	11.8	4.4	9.7	2.4	7.8	9.1	8.3	5.9
f_{ip} (%)	96.2	85.3	75.3	93.1	94.2	55.7	75.1	96.2	82.6	76.4	73.6	76.3	88.9	70.0
s_{ip} (%)	87.9	70.5	71.1	69.8	89.2	64.3	53.8	60.4	68.6	80.6	57.2	86.7	63.8	72.0
LL_{ip} (%)	92	85	87	91	92	82	85	95	87	82	97	91	80	78
FL_{ip} (%)	70	50	50	80	80	60	60	70	60	80	50	70	70	80

respectively in Table 4. The objective is to find the best structure of the VE and assign the optimal order allocation to the most appropriate partners in order to fulfill the customer BO.

Firstly, the Fuzzy ANP technique is implemented in order to determine the weights of the partner evaluation criteria. After a discussion with the customer, the broker forms the pairwise comparisons of decisions elements of the ANP network shown in Figure 3. After this step, the unweighted super-matrix is obtained. Then, the relationship level among main criteria is determined. The multiplication of the criteria priorities with the unweighted super-matrix gives the weighted super-matrix. The final step is the calculation of the limit super-matrix. All calculations are performed using *SuperDecision* software. According to the assumed BO, the obtained weights of the partner selection criteria are $W_j = (W_C, W_Q, W_S, W_L, W_O, W_E, W_F) = (0.418, 0.155, 0.035, 0.032, 0.036, 0.244, 0.08)$.

Subsequently, the mathematical programming model developed in Section 4.2 is applied in order to create the optimal VE by determining the suitable orders allocation to the suitable partners. The mathematical model is formulated in *LINGO 17.0* software. In fact, each objective function is solved separately with respect to the constraints shown in equations (4.8)–(4.13) in order to calculate the optimal solution of each objective. After that, using criteria weights obtained as well as the optimal value of objectives, the objective function shown in equation (4.23) is solved under constraints shown in equations (4.8)–(4.13). The programming results are shown is Tables 5 and 6. In fact, the selected partners and the order allocated for each one of them is shown in Table 5. Table 6 presents the achieved values of the different objective functions. The set of partners P_2, P_3, P_9

Table 5. The decision variable Y_{ip} results (Example 1).

Y_{ip}	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}
Sub-project 1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sub-project 2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Sub-project 3	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Sub-project 4	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Table 6. Achievement of objectives for the whole VE configured (Example 1).

Objectives	Performance
Cost	32 6000$
Quality level of sub-projects	78.3%
Service level of partners	70.55%
Lead time of sub-projects	Total of sub-projects: 28.5 Months Lead time of BO = Max (Lead times of Si) = 9.7 Months
On-time delivery of sub-projects	84.25%
Establishment cost	8181$
Flexibility level of partners	60%

and P_{14} are then announced as the best partners of the VE consortium for the achievement of respectively the BO sub-projects S_1, S_2, S_3 and S_4. This combination of partners is the optimal possible ones according to the customer's preferences and requirements. For another BO with different customer requirements and different preferences, the results will obviously change.

5.1.2. Example 2

In the second example, it is assumed that a partner can submit for more than one sub-project. Let's consider the BO of the first example. In this case, five enterprises are considered to be qualified for each sub-project. Detailed information bided for each sub-project and its corresponding calculations are presented in Table 7.

Using the same objective weights of the first example, the best partners and the optimal order allocation for each one of them are obtained. As shown in Table 8, a novel VE consortium is created for the achievement of the BO, which is different to the VE created in the first example. Further, the achieved values of the different objective functions shown in Table 9 are more efficient than those obtained in the first case (Table 6). For instance, the total cost of the second case (31 9381$) is more optimal than the first one (33 4181$) when the delivery time of the BO increases from 9.7 months to 9.8 months. Thus, the proposal of the second case is more profitable as long as the BO deadline is respected. In addition, the quality in the second example is more performant than the first one. In fact, the quality level is improved by 7.36% as well as the service level by 20.22%. The obtained results are interesting seeing that the quality is an important factor to meet the customer satisfaction. Moreover, in terms of flexibility level and on-time delivery, the allocation of more than one sub-project to the same partner is more efficient since they are improved by, respectively 6.25% and 29.16%. Therefore, it should be noted that increasing the number of partners' bids may make the results more efficient.

The proposed approach represents a decision support mechanism that helps the DM to optimize his decisions based on weighted selection criteria. Hence, it guarantee the objectivity of decisions and so the success of the VE configuration in meeting BO requirements.

TABLE 7. The processing cost, the transport cost, the partner's capacity, the lead time, the quality level, the service level, the on- time delivery and flexibility level of each partner (Example 2).

	S_1					S_2				
	P_1	P_2	P_9	P_{12}	P_{14}	P_3	P_4	P_5	P_6	P_7
C_{ip} (10^3\$)	85.3	74.6	73.5	79.8	78.6	55.5	82.6	91.2	63.2	51.6
CT_{ip} (10^3\$)	5.3	3.1	2.8	35	4.6	4.1	3.7	2.6	3.8	2.0
Cap_{ip} (Number of units)	250	300	300	320	250	100	110	150	130	80
lt_{ip} (Month)	8.8	5.3	9.8	5.2	5.1	7.6	4.5	8.9	10.5	11.8
f_{ip} (%)	96.2	85.3	90	87.5	89.5	75.3	93.1	94.2	55.7	75.1
Sip (%)	87.9	70.5	85.3	71.2	97.5	71.1	69.8	89.2	64.3	53.8
LL_{ip} (%)	92	85	90	87	92	87	91	92	82	85
FL_{ip} (%)	70	50	80	70	60	50	80	80	60	60
	S_3					S_4				
	P_8	P_9	P_{10}	P_{11}	P_2	P_{12}	P_{13}	P_{14}	P_5	P_7
C_{ip} (10^3\$)	99.4	96.5	86.4	92.9	85.9	89.7	90.2	84.0	83.9	82.5
CT_{ip} (10^3\$)	2.8	2.5	4.2	5.5	2.7	4.9	3.6	5.7	3.9	4.2
Cap_{ip} (Number of units)	170	220	190	210	300	150	120	80	150	100
An lt_{ip} (Month)	4.4	9.7	2.4	7.8	9.8	9.1	8.3	5.9	7.2	7.5
f_{ip} (%)	96.2	82.6	76.4	73.6	80.5	76.3	88.9	70.0	89.5	90.5
s_{ip} (%)	60.4	68.6	80.6	57.2	85.6	86.7	63.8	72.0	87.6	97.3
LL_{ip} (%)	95	87	82	97	90.0	91	80	78	84	92
FL_{ip} (%)	70	60	80	50	90	70	70	80	80	90

TABLE 8. The decision variable Y_{ip} results (Example 2).

Y_{ip}	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}
Sub-project 1	0	0	0	0	0	0	0	0	1	1 0	0	0	0	0
Sub-project 2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Sub-project 3	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sub-project 4	0	0	0	0	0	0	1	0	0	0	0	0	0	0

TABLE 9. Achievement of objectives for the whole VE configured (Example 2).

Objectives	Performance
Cost	31 1200\$
Quality level of sub-projects	84.07%
Service level of partners	84.82%
Lead time of sub-projects	Total of sub-projects: 34.7 Months Lead time of BO = Max (Lead times of Si) = 9.8 Months
On-time delivery of sub-projects	89.75%
Establishment cost	8181\$
Flexibility level of partners	77.5%

TABLE 10. Sub-projects demand (Case study).

	S_1	S_2	S_3	S_4	S_5	S_6
D_i (Number of units)	590	1132	1580	250	700	600

5.2. Case study

The studied case is a supply network of SME enterprises from a textile industry located in Tunisia. The network is composed of one company (TExtile INTERnational "TE-INTER") and eight partners, who are an embroiderer, a printer, a dyer and five cloth makers. Each partner has a specific role according to the field of his activity. Printing, dyeing and embroidery activities are three intermediate operations, while both inputs and outputs represent semi-finished products. Cloth makers take part in the final steps of the manufacturing process. They convert the semi-finished products received from TE-INTER into finished products that are returned to the company for delivery to the final customers.

When faced to BOs, TE-INTER subcontracts a set of activities for two reasons. The first reason is the lack of competence in the fields of dyeing, printing and embroidery. The second reason consists of the need for extension of production capacity to fulfill all the customers' orders, which raises the need for collaborating with cloth making partners. In fact, the core competences of TE-INTER and the cloth makers are similar. In this respect, the focus of the present case study is on the relationship between TE-INTER and the five cloth makers. TE-INTER plans and executes some of the cloth making activities and allocates some operations to one or more of its partners. In this context, TE-INTER CEO is the broker who should select the appropriate partners and their association form a VE. According to two previous studies [23, 24], the partner assessment process considered by TE-INTER to configure corresponding VE is mainly based on trust-related criteria. These criteria represent strategic concepts and this assessment process should so be revised. Therefore, the approach proposed in this paper is helpful for TE-INTER in order to better react when faced to specific BOs.

As part of the case study, an interview is organized with TE-INTER CEO who is the DM (or broker). A questionnaire is designed to collect data related to the evaluation criteria and partners' performances. The considered selection criteria represent a basis for the questionnaire formulation. The first objective of this questionnaire is the identification of broker preferences toward partner selection criteria for a specific BO. These information are then analyzed in order to determine the criteria weights. The second objective of the questionnaire is gathering information related to partners in order to calculate the mathematical model parameters presented in Section 4.2.

The BO, object of the case study, consists of a particular summer season related orders. The orders cover different cloth requests from several customers. The BO is decomposed into six sub-projects ($N = 6$). The demand of each sub-project is presented in Table 10. The required deadline of the BO is three months. Since the cloth making is an intermediate activity between previous activities and the packaging operation, the TE-INTER planner planned one month to the cloth making operations.

The first step is to determine the selection criteria weights corresponding to the BO. The set of criteria presented in the Table 1 are accepted by the company DM excluding the establishment flexibility criterion, thus it is not considered. In addition, the performing and transportation costs are represented by a single aggregated value proposed by the partners. With respect to the implementation of the Fuzzy ANP technique, series of questions for pairwise comparisons are responded by the DM. For instance, Table 11 shows the DM's evaluation of main criteria with respect to its contribution to the objective, which is the selection of suitable partners for the BO. An evaluation of sub-criteria toward its main criteria is also performed in order to determine the local weights of sub-criteria.

Subsequently, the interdependence among the ANP network elements, shown in Figure 3, is considered to examine the relative impact of all sub-criteria against each other. Pairwise comparisons are designed to prioritize

TABLE 11. Pairwise comparison matrix for main criteria in terms of the goal.

Linguistic pairwise comparison					Corresponding TFN				Local weights
Goal	*D*	*Q*	*F*	*C*	*D*	*Q*	*F*	*C*	
D	EI	1/I	IM1	IM1	(1, 1, 1)	(1/6, 1/5, 1/4)	(1, 2, 3)	(1, 2, 3)	0.170
Q	I	EI	IM3	I	(4, 5, 6)	(1, 1, 1)	(5, 6, 7)	(4, 5, 6)	0.627
F	1/IM1	1/IM3	EI	1/IM1	(1/3, 1/2, 1)	(1/7, 1/6, 1/5)	(1, 1, 1)	(1/3, 1/2, 1)	0.083
C	1/IM1	1/I	IM1	EI	(1/3, 1/2, 1)	(1/6, 1/5, 1/4)	(1, 2, 3)	(1,1, 1)	0.120
$\lambda * = 0.035$									

TABLE 12. The unweighted super-matrix.

		D		*Q*		*F*	*C*
		D_1	D_2	Q_1	Q_2	F_1	C
D	D_1	0.000	0.000	0.333	0.250	0.000	0.800
	D_2	0.000	0.000	0.667	0.750	0.000	0.200
Q	Q_1	0.900	0.800	0.000	0.000	0.000	0.900
	Q_2	0.100	0.200	0.000	0.000	0.000	0.100
F	F_1	1.000	1.000	1.000	1.000	0.000	1.000
C	C	0.000	0.000	1.000	1.000	1.000	0.000

the sub-criteria with respect to all related criteria ones. These comparisons give the unweighted super-matrix shown in Table 12.

After that, a weighted super-matrix is calculated by combining the unweighted super-matrix and the cluster matrix. The limiting super-matrix is then obtained through the multiplication of the weighted super-matrix by itself. The sequence of the evaluation criteria according to its priorities is shown in Figure 4. In fact, according to the case study, the partner evaluation is essentially based on quality level, whose corresponding weight is equal to 0.308. This is obvious since there is no margin for error in terms of quality within the company. In fact, customers require products with very high quality level. Although the importance of cost criterion, its weight (equal to 0.21) is less than the quality one. This can be explained by the fact that bidders proposed by partners have usually approximate costs. The following sub-criteria are respectively on-time delivery and flexibility level, whose corresponding weights are almost equal. In fact, the respect of delivery times is less important than quality and cost since negotiation with customers about flexible deadlines is worth considering. However, this criterion has the third importance in partner evaluation criteria since delivery lateness can cause additional fees related to transportation costs or late payment penalty in case of repetitive lateness. Further, the importance of the flexibility level is justified by the short shelf-life of fashion textile products. In this case study, the lead time and the service level sub-criteria has low importance in partner evaluation. In fact, partner lead time can be flexible and negotiated as long as it allows TE-INTER to respect the deadline required by customers. In addition, the partners are always ready to give TE-INTER orders the priority in their planning, since this enterprise represents their potential partner.

After determining the weights of the evaluation criteria, the selection procedure starts with the search in the VBE by detecting the members who are able to work the corresponding sub-projects. In fact, each partner is distinguished from the others with particular technical competencies in the cloth making filed. The search in VBE pool of entities results that there are four members qualified for sub-project S_1 (P_1, P_2, P_3 and P_4), three for sub-projects S_2 and S_6 (P_1, P_2 and P_5) and two for sub-projects S_3, S_4 and S_5 (P_1 and P_2). The main scope of this research is to select the most appropriate partner for each sub-project. The five partners submit their

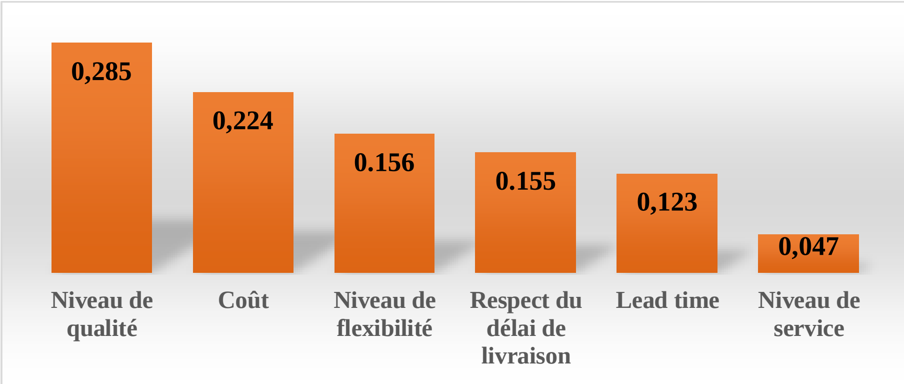

FIGURE 4. Weights of the tactical partner selection criteria.

TABLE 13. The processing cost, the partner's capacity and the lead time of each partner (Case study).

	S_1				S_2			S_3	
	P_1	P_2	P_3	P_4	P_1	P_2	P_5	P_1	P_2
C_{ip} (DT)	3000	3000	2400	2400	1700	1700	1500	3000	3000
Cap_{ip} (Number of units)	1000	1000	590	590	1500	1500	2000	2000	2000
lt_{ip} (Week)	2	1	3	2	3	2	2	3	3
		S_4		S_5		S_6			
		P_1	P_2	P_1	P_2	P_1	P_2	P_5	
C_{ip}(DT)		4000	4000	5700	5700	2200	2200	1800	
Cap_{ip} (Number of units)		500	500	1000	1000	1000	1000	1500	
lt_{ip} (Week)		3	1	1.5	1	1	2	1	

TABLE 14. The quality level, the service level, the on-time delivery and flexibility level of each partner (Case study).

	P_1	P_2	P_3	P_4	P_5
f_{ip}(%)	95	95	90	90	70
s_p(%)	80	30	50	80	85
LL_{ip}(%)	85	95	85	90	70
FL_{ip}(%)	95	40	75	90	95

bids characterized by corresponding costs, capacity and lead time for fulfilling sub-project i. The background information in terms of quality, service and flexibility levels and on-time delivery degree are provided by the company DM based on previous projects. The values of these parameters are useful for all sub-projects. All of data are gathered in Tables 13 and 14.

Using the collected data, the mathematical model presented in Section 4.2 is generated seven times. In fact, each of the six objectives functions (4.1)–(4.5) and (4.7) are solved individually under constraints shown in equations (4.8)–(4.13) in order to determine the optimal solution of each objective. We remind that in this case study the criterion corresponding to the objective function (4.6) is removed. The obtained values as well as the identified criteria weights are incorporated in the objective function presented in equation (4.23), which is solved under constraints shown in equations (4.8)–(4.13). The results are shown in Table 15. The best VE consortium sets {partner, sub-project} to achieve the BO are respectively $\{P_4, S_1\}$, $\{P_5, S_2\}$, $\{P_1, S_3\}$, $\{P_2, S_4\}$, $\{P_1, S_5\}$ and $\{P_1, S_6\}$.

The partner P_4 is selected for performing the sub-project S_1 since the demand is low and he has a low capacity. In addition, he is perfect in terms of quality and flexibility. The Partner P_5 is selected for performing the sub-project S_2 since his proposed cost and lead time are less than others partners. Moreover, he is always available and flexible in terms of operations and time despite his quality level is not perfect. In fact, the sub-project S_2 does not require a cloth maker mastering high qu1ality degree since the design of corresponding product is so simple. The partner P_2 is selected for performing the sub-project S_4 because he proposed the lowest lead time despite he is swamped with his own work. In addition, he is perfect in terms of quality, flexibility and delivery. The partner P_1 is the most solicited one in the BO. He is designated for completion of sub-projects S_3, S_5 and S_6. In fact, he participated in several previous BOs and showed high quality and flexibility levels as well as high service level.

The developed methodic approach is considered by the TE-INTER DM as a helpful tool that supports an objective evaluation of partners. Moreover, the DM believes that the consideration of the criteria as well as its corresponding weights can strengthen the credibility of the assessment and selection process. In addition, the proposed approach allowed TE-INTER DM to identify partner assessment criteria that should be improved by each of their collaborators in order to increase their chance of participation in BOs. This fosters the commitment of the partners for an efficient integration in the supply network and for a better understanding and reply to specific needs of customers.

6. Conclusion

This paper proposes a two-stage methodology to address the PS problem and order allocation optimization for the purpose of VE configuration from a VBE to respond to a BO. In the first stage, the convenient tactical criteria and sub-criteria are identified. Then, a Fuzzy ANP technique is used to identify the criteria weights based on customer's preferences and requirements. In the second stage, the criteria weights obtained are incorporated into a MOP model to evaluate the partners and then select the most appropriate of them for the achievement of the BO. The solution of the problem is obtained using the WSM.

This study contributes to the literature from three perspectives. First, it tackles an important issue of the partner selection process that is the design of a new combination and exhaustive classification of the partner evaluation criteria in the context of VE configuration from VBE. Second, the proposed MOP is used to face the trade-offs between seven objective functions with different weights. Third, the development of a fuzzy decision support mechanism helps to objectively assess partners and then identify the most appropriate members for such a short-term partnership. The vagueness of evaluation process is tackled using fuzzy logic.

The applicability of the proposed approach is elucidated using two illustrative examples and a case study from textile industry. It is demonstrated that the proposed mathematical formulation is flexible enough to enables the investigation of different scenarios. In fact, it is possible to attribute different weights to the criteria with respect to considered BO and corresponding customer preferences and requirements. In addition, the case study reveals that a specific objective function for such collaboration context could be included or removed without greatly having to alter the original model. The industrial feedback confirms the objectivity and the efficiency of the proposed methodic approach in assessing and selecting partners.

To advance the contributions of this study, the proposed approach could be extended to make the possibility of performing each sub-project by more than one partner in case of limited capacities of individual organizations, especially in extreme customer requirements such as tight delivery time for high demand volumes. Furthermore, the implementation of the ANP technique necessitates several pairwise comparisons. This may be onerous and a time consuming for industries. Therefore, a development of a database, in which the priorities of the criteria are recorded according to the activity filed or to the customer, would help the DM to quickly make the best decisions. This database could be updated after a time period to be fixed by VBE members.

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