International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713696255

Partner selection in virtual enterprises

José António Crispim [a]; Jorge Pinho de Sousa [b]
[a] Department of Management, University of Minho, Braga, Portugal [b] INESC Porto/Faculty of Engineering, University of Porto, Porto, Portugal

First published on: 14 November 2008

To cite this Article Crispim, José António and de Sousa, Jorge Pinho(2010) 'Partner selection in virtual enterprises', International Journal of Production Research, 48: 3, 683 — 707, First published on: 14 November 2008 (iFirst)
To link to this Article: DOI: 10.1080/00207540802425369
URL: http://dx.doi.org/10.1080/00207540802425369

International Journal of Production Research
Vol. 48, No. 3, 1 February 2010, 683–707

Partner selection in virtual enterprises

José António Crispim[a]* and Jorge Pinho de Sousa[b]

[a]*Department of Management, University of Minho, Braga, Portugal;*
[b]*INESC Porto/Faculty of Engineering, University of Porto, Porto, Portugal*

(*Received 11 December 2007; final version received 28 April 2008*)

A virtual enterprise (VE) is a temporary organisation that pools member enterprises core competencies and exploits fast changing market opportunities. VEs offer new opportunities to companies operating with a growing number of participants (consumers, vendors, partners and others) in a global business environment. The success of such an organisation is strongly dependent on its composition, and the selection of partners therefore becomes a crucial issue. Partner selection can be viewed as a multi-criteria decision making problem that involves assessing trade-offs between conflicting tangible and intangible criteria, and stating preferences based on incomplete or non-available information. In general, this is a very complex problem due to the large number of alternatives and criteria of different types (quantitative, qualitative and stochastic). In this paper we propose an integrated approach to rank alternative VE configurations using an extension of TOPSIS (a technique for ordering preferences by similarity to an ideal solution) for fuzzy data, improved through the use of a tabu search meta-heuristic. A sensitivity analysis is also presented. Preliminary computational results clearly demonstrate the potential of the approach for practical application.

Keywords: virtual enterprises; meta-heuristics; multi-attribute decision-making; TOPSIS

1. Introduction

A virtual enterprise (VE) is a temporary alliance of independent and geographically dispersed enterprises set up to share skills or core competencies and resources in order to respond to business opportunities, the cooperation among the enterprises being supported by computer networks (Camarinha-Matos and Afsarmanesh 2003). This is considered one of the most promising business strategies for enterprises to face global competition (Chen *et al.* 2007) and it is meaningful in quite different contexts such as manufacturing, healthcare, tourism, transportation and others. The success of such an organisation is strongly dependent on its composition. In this context, the selection of the right partners is crucial. The creation of a VE is usually triggered by an emerging market opportunity, giving rise to a 'project' that is decomposable in relatively independent sub-projects or activities. Therefore, before a VE is formed, the different inputs and outputs of each activity have to be clearly defined. The cooperation relationship can be represented by an activity network with precedence. The problem of partner selection also arises when the

*Corresponding author. Email: crispim@eeg.uminho.pt

ISSN 0020–7543 print/ISSN 1366–588X online

DOI: 10.1080/00207540802425369
http://www.informaworld.com

VE needs to be reorganised by adding/expelling some members or by reassigning tasks or roles in order to better cope with new market circumstances.

In this paper the focus is on developing a flexible multi-project/multi-period decision support tool to help the decision maker (DM) during the partner selection process. These questions, multi-period dynamics and flexibility, are very important in the VE research field because of the temporary distinctive nature of this type of collaboration.

The proposed approach presents a hybrid algorithm that selects the partners taking a given horizon into consideration and uses, for the first time in this field (to the best of our knowledge), a multi-objective multi-period metaheuristic combined with the TOPSIS technique in a fuzzy environment, to search and rank non-dominated potential VE configurations.

The flexibility of the approach arises from the possibility of choosing different objectives and constraints for each project and from the variety of variable types that the DMs can use to express their preferences. In general, in the previously published works, flexibility is small because the models are adjusted to a network with specific characteristics, e.g., operational costs (Ma *et al.* 2007) or risk factors (Li and Liao 2007). This can be observed when we look at other methodologies that have been applied to solve the partner selection problem such as mathematical programming (Dotoli *et al.* 2006) or fuzzy mathematical programming (Araz *et al.* 2007), where the decision problem is formulated mathematically. The drawbacks of this lack of flexibility are even more apparent when we are forming a VE, because the decision environment can change a lot.

Other approaches require an intensive participation of the DM. This is, for example, the case of AHP, where the DM is required to perform pair-wise comparisons between the criteria and the supplier alternatives (e.g., Sari *et al.* 2007). In order to overcome this inconvenience and to maintain the quality of the original data, we do not aggregate information, and therefore we do not make use of weights in the search phase. We believe that it is difficult for the DM, in this early phase where the solution space can be quite vast (the number of alternatives tends to infinite), to set weights on a realistic level and to understand the interdependencies among the objective functions. Different weights provide different solutions but the same solution can be generated by different weights, and this may be confusing to the DM. Consequently, we have chosen the Pareto non-dominated concept to perform our search (a solution is Pareto optimal if there are no other feasible solutions with higher value of some objectives without a lower value in at least one other objective). We only use weights at the final stage because we want the DMs to rank the criteria importance, using their expertise or experience, so that the obtained solutions are closer to their ideals.

In terms of information gathering, we know that the selection and evaluation of partners is a difficult problem due to the complex interactions between the different entities and because the expression of their preferences may be based on incomplete or partially non-available information. To deal with this problem under a multi-criteria perspective, we allow several types of information (numerical, interval, qualitative and binary) in order to facilitate the expression of the stakeholders' preferences or assessments about the potential partners. This is an important requirement in practice as the multiplicity of factors considered when selecting partners for a business opportunity such as cost, quality, trust and delivery time, cannot be expressed in the same measure or scale. In general, partner selection approaches do not use mixed types of variables, applying only fuzzy numbers (e.g., Cao and Zhou 2006), or linguist terms (e.g., Lin *et al.* 2007), or numbers, indexes and ratios (e.g., Sari *et al.* 2007). In cases where there is an attempt to use both quantitative and qualitative information, there is usually a prior lack of flexibility, as we are forced to pre-define the scale cardinality (e.g., 9-scale or five-point likert scale, Araz *et al*. 2007).

The remainder of the paper is organised as follows. In Section 2 the problem is described, in Section 3 the literature on the domain is briefly surveyed, in Section 4 the method used to solve the problem is presented, in Section 5 an illustrative example is described and finally, in Section 6 some preliminary conclusions are presented.

2. Problem description

Assume a network representing all potential partners (companies) and their relationships. A specific entity is responsible for the VE formation process (this entity is here referred to as the decision maker or DM). Companies and relationships are characterised by a set of criteria, some assigned to the nodes and some assigned to the edges of the network. Part of these criteria will define the objectives and the constraints of the problem. The first step in this modelling process is to carefully define what criteria are going to be considered in both subsets. The DM will assign weights to the objectives according to his/her beliefs about their relative importance for the project under consideration.

The network includes a set of companies (nodes) connected with each other, capable of performing activities and of providing a finite amount of resources, available over specific intervals of time. From detected market opportunities, projects are created. A project involves a set of activities that demand a specific amount of resources and have to be performed within a given time interval. These activities have a number of precedence relationships and therefore form an activity network.

Then the partner selection problem consists of choosing the best group of companies to perform all activities of a given project(s) taking into account a set of objectives and constraints (Figure 1). The main constraints of the problem are *time windows* and the *minimum amount of resources* required.

In the following we present a general model for the problem:

Indices

$t = 1, \ldots, T$ time periods.
$j = 1, \ldots, N$ candidates (companies).

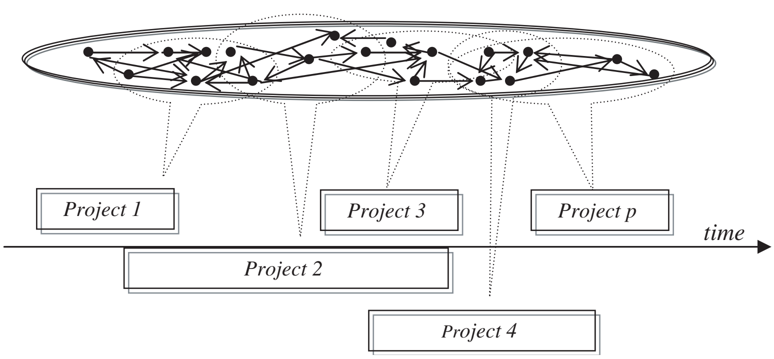

Figure 1. Multiple projects in a network and VEs.

$m = 1, \ldots, M$ criteria.
$h = 1, \ldots, H$ activities that a network is capable of performing.
$p = 1, \ldots, P$ projects.

Parameters

l_{mj}: score (contribution) of criterion m for candidate j: l^o_{mj} for objective criteria; l^c_{mj} for constraint criteria.
d_{ip}: processing time of activity i of project p.
$O_{ip} = [s_{ip}; f_{ip}]$: time window (interval) to perform activity i of project p.
D_p: due time to perform the project p.
A_p: set of activities in the project p.
Q_{ip}: quantity of resources needed to perform activity i of project p.
$V_j = [u_j; y_j]$: interval of time in which candidate j is available.
r_{jt}: capacity (available quantity of resources) of candidate j in period t.
W_i: set of candidates for performing activity i.
B_p: maximum possible investment for project p (budget).
b_{ij}: cost of performing activity i by candidate j.

Decision variables

$$x_{ijt} = \begin{cases} 1 & \text{if activity } i \text{ is contracted to candidate company } j \text{ for period } t \\ 0 & \text{otherwise} \end{cases}.$$

Objective functions

We consider multiple objectives such as cost, quality, flexibility, etc. represented by $z_1, z_2, \ldots, z_m, \ldots$:

$$\max z_1 = \sum_t^T \sum_i^{A_p} \sum_j^{W_i} l^o_{1j} x_{ijt}, \quad \forall p \in P \tag{1}$$

$$\max z_2 = \sum_t^T \sum_i^{A_p} \sum_j^{W_i} l^o_{2j} x_{ijt}, \quad \forall p \in P \tag{2}$$

$$\max z_m = \sum_t^T \sum_i^{A_p} \sum_j^{W_i} l^o_{mj} x_{ijt}, \quad \forall p \in P. \tag{3}$$

Constraints

$$\sum_i^{A_p} \sum_j^{W_i} \sum_t^{d_{ip}} x_{ijt} b_{ij} \le B \quad \forall p \in P \tag{4}$$

$$\sum_j^{W_i} \sum_t^{d_{ip}} x_{ijt} r_{jt} \le Q_{ip} \quad \forall p \in P, \ \forall i \in A \tag{5}$$

$$\sum_t^{d_{ip}} \sum_j^{W_i} x_{ijt} f_{ip} \le \sum_t^{d_{kp}} \sum_j^{W_k} x_{kjt} s_{kp}, \quad \forall i, k \in A \text{ and } i \text{ preced } k, \ \forall p \in P \tag{6}$$

$$\sum_{t}^{d_{sp}} \sum_{j}^{W_s} x_{sjt} f_{sp} \leq D_p \quad \forall s \in A,\ \forall p \in P \tag{7}$$

$$\sum_{t}^{d_{ip}} \sum_{j}^{W_i} x_{ijt} = 1, \quad \forall i \in A,\ \forall p \in P \tag{8}$$

$$u_j \leq f_i - d_i, \quad \forall i \in A,\ \forall j \in W \tag{9}$$

$$y_j \geq s_i + d_i, \quad \forall i \in A,\ \forall j \in W \tag{10}$$

$$\sum_{t}^{d_{ip}} \sum_{j}^{W_i} x_{ijt} l_m^c \geq C_p, \quad \forall i \in A, \forall p \in P. \tag{11}$$

Constraints (4) state that the sum of costs cannot be larger than the global budget for the project under analysis. Constraints (5) impose that candidate j, if contracted to perform activity i in period t, can provide up to Q_{ip} units of the product in that period. Constraints (6) impose the precedence relationships between activities, i.e., states that, for two activities i and k with a precedence relation, execution of k (s_{kp}) can only begin after i finishes. Constraints (7) ensure that the project is completed no later than the project deadline, i.e., the last activity of the project s must be equal or less than the project due time. Constraints (8) impose that, for any period for a given activity, only one candidate (or group of enterprises working as an individual element) can be selected. Finally, constraints (9) and (10) ensure that the time interval when the resources of candidate j are available fits the 'time window' for activity i (Figure 1), and constraints (11) impose that, for each additional constraint, a minimum (maximum) value has to be accomplished. Other constraints, related to third party logistics (3PL), might be included but, as an alternative, these aspects can be covered by the objective function, considering some additional criteria.

3. Literature review

A review of the literature about partner selection methods in various research contexts (such as supply chain design, agile manufacturing, network design, dynamic alliances, and innovation management) has been performed in order to investigate the distinct approaches used to tackle this problem. We have concentrated this survey on research based on mathematical or quantitative decision-making approaches published in recent years (since 2001), and have grouped those approaches according to the methodology adopted. The survey included 57 papers covering quite different perspectives.

Three classification criteria have been adopted for categorising the reviewed articles:

- *Research context*: virtual enterprise/dynamic alliance, manufacturing, and supply chain/network.
- *Methods used to solve the problem* (almost all the research papers we found use hybrid algorithms).
- *Criteria/factors* on which the partner selection is based.

The findings from this survey (57 papers) can be summarised as follows:

(1) Seventy-four percent of the papers were published in the last two years (since 2005).
(2) In terms of research context (Table 1), 51% of the papers are on virtual enterprises, 17% on manufacturing, and 32% on supply chains. Although there is a large number of papers published in this area (supply chain, network design), many of them have not been considered in the survey because they do not tackle partner selection as an isolated problem, but try rather to optimise or create a chain/network configuration considering questions such as localisation, inventory management and/or transportation.
(3) Although 90% of the papers describe hybrid methodologies, the quantitative approaches to partner selection can nevertheless be grouped into three main categories: optimisation approaches (exact and heuristic algorithms) – 56%; multi-criteria decision aiding (such as AHP, MAUT, fuzzy set theory) – 33%; and other methods such as simulation or clustering – 11%. Within optimisation approaches 63% are on heuristic algorithms and 37% on exact algorithms. Genetic algorithms are very popular within heuristic approaches (70%), and only two in 13 articles use tabu search as an alternative method. The 'main' algorithm is often combined with contributions from fuzzy set theory, because of the ill-defined nature of the selection process. In MADM, the combination of fuzzy numbers with AHP is the most frequent.
(4) Criteria may be grouped into two main classes (Table 2): a) risk (e.g., political stability, economy status of the region, financial health, market fluctuations, competency), costs and time factors (35%); and b) other attributes (such as trust, technology level, capacity resources, organisation structure, financial status, past performance, quality, etc.). In this last group: a) 49% use quantitative information expressed by numbers, percentages or performance indices; b) 19% use numerical scales; c) 11% use fuzzy numbers to deal with the vagueness of the DM preferences; and d) 22% use linguistic terms to facilitate the expression of DM preferences. Usually the linguistic terms are fuzzified, i.e., transformed in fuzzy sets.

From this survey, it is also possible to draw some useful preliminary conclusions about the main research trends for partner selection in a virtual enterprise context, namely these are:

- An enormous concern about optimising the solution, i.e., to select the right partner.
- A need to obtain complete and diversified information (multiple attributes) about each potential partner.
- Subjectivity in the data.
- A need to facilitate the expression of the decision maker's assessments about the potential partners.
- A real concern with dynamic aspects (i.e., time dependent issues).

4. Developed approach

The classic model based on risk and cost factors is a 0–1 integer programming with a nonlinear objective and several inequality and equality constraints (Cao and Gao 2006).

Table 1. Research context/methods organisation.

Method	Research context		
	Virtual enterprise/ dynamic alliance	Manufacturing	Supply chain
Heuristic algorithms			
Genetic algorithm	Ma *et al*. (2007)	Cao and Gao (2006)	
+particle swarm optimisation		Zhao *et al*. (2006b)	
+fuzzy set theory	Tang *et al*. (2006)	Wang *et al*. (2001)	Lin and Chen (2004)
	Zhao *et al*. (2004)	Zhao *et al*. (2006c)	
	Ip *et al*. (2003)		Wang and Lin (2006)
	Zhao *et al*. (2006a)		
+Dempster-Shafer theory	Yang *et al*. (2006)		
+On-line analytical processing			Ho *et al*. (2006)
+AHP and MAUT			Sha and Che (2006)
Tabu search		Ko *et al*. (2001)	
+2-tuple fuzzy linguistic representation model	Crispim and Sousa (2005)		
+TOPSIS	Crispim and Sousa (2007)		
ACO (Ant colony optimisation) + AHP	Kang *et al*. (2007)		
Particle swarm optimisation	Gao *et al*. (2006)		
Local search algorithm	Chen *et al*. (2007)		
Exact algorithms			
Integer programming model	Ip *et al*. (2004) – B&B		Dotoli *et al*. (2006)
+2-phase improvement algorithm		Wu and Su (2005)	
+AHP and MAUT		Sha and Che (2005)	
Mixed-integer programming model	Jarimo and Pulkkinen (2005)	Viswanadham and Gaonkar (2003)	Gaonkar and Viswanadham (2004)

(*continued*)

Table 1. Continued.

	Research context		
Method	Virtual enterprise/dynamic alliance	Manufacturing	Supply chain
Multi-objective mixed-integer programming model	Jarimo *et al.* (2006)		
Nonlinear integer programming with branch-and-bound algorithm (B&B)	Zeng *et al.* (2005)		
Fuzzy goal programming +PROMETHEE			Araz *et al.* (2007)
Weighted linear program			Ng (2008)
Goal programming model			Hajidimitriou and Georgiou (2002)
Fuzzy set theory			
+evidential reasoning	Li and Liao (2007) Liao and Tang (2003)		
+AHP	Cao *et al.* (2004) Cao and Zhou (2006) Mikhailov (2002)		Kahraman *et al.* (2003)
+clustering	Dai and Yang (2005)		
+critical path analysis	Huang *et al.* (2005)		
Fuzzy comprehensive evaluation	Huang and Chen (2005)		
Consistent fuzzy preference relations	Wang and Chen (2007)		

Fuzzy inference system			Carrera and Mayorga (2008)
Fuzzy TOPSIS			Chen *et al*. (2006)
Fuzzy decision-making model	Ye and Li (2005) Ren *et al*. (2007)		Lin *et al*. (2007)
Analytic hierarchy process (AHP)			
AHP	Sari *et al*. (2007)		
+multi-objective mixed integer programming			Xia and Wu (2007)
+TOPSIS			Büyüközkan *et al*. (2008)
+SCOR model	Bettencourt and Rabelo (2005)		
Others			
Simulation optimisation methodology	Kim *et al*. (2006)	Heavy *et al*. (2006)	Ding *et al*. (2006)
CLIQUE cluster analysis			Xu *et al*. (2006)
Two-stage manufacturing partner selection framework		Huang *et al*. (2004)	
Multi-level approach: first level: candidate selection; second level: network design; third level: solution evaluation and validation			Dotoli *et al*. (2005)

Table 2. Criteria on which the partner selection is based.

	Criteria	Article
Risk factors		Ye and Li (2005)
		Huang and Chen (2005)
		Jarimo and Pulkkinen (2005)
		Li and Liao (2007)
		Zhao *et al*. (2006c)
	+due date and performance	Yang *et al*. (2006)
		Zhao *et al*. (2004)
		Zhao *et al*. (2006b)
Operational costs	+time to market + performance	Gaonkar and Viswanadham (2004)
		Viswanadham and Gaonkar (2003)
	+financial costs	Ip *et al*. (2004)
	+transportation costs	Ko *et al*. (2001)
	+due date	Cao and Gao (2006)
	+processing time	Wang *et al*. (2001)
		Wu and Su (2005)
	+service level	Ding *et al*. (2006)
	+processing time + efficiency	Huang *et al*. (2005)
	+completion time of subprojects + due date	Zeng *et al*. (2005)
	+time + credit	Ma *et al*. (2007)
	+ reaction time + risk factor	Gao *et al*. (2006)
Multiple criteria expressed by:	fuzzy numbers	Cao *et al*. (2004)
		Cao and Zhou (2006)
		Wang and Lin (2006)
		Kahraman *et al*. (2003)
	interval pairwise comparisons	Wang and Chen (2007)
	verbal judgements transformed in scale (1–9)	Sha and Che (2005)
		Kang *et al*. (2007)
	numerical scale (1–5; 1–9;...)	Hajidimitriou and Georgiou (2002)
		Huang *et al*. (2004)
		Cao *et al*. (2004)
		Cao and Zhou (2006)
		Mikhailov (2002)
	operational performance indices	Dotoli *et al*. (2005)
		Dai and Yang (2005)
		Sha and Che (2006)
		Ho *et al*. (2006)
	linguistic terms and performance ratio measures	Araz *et al*. (2007)
	linguistic terms	Lin *et al*. (2007)
		Büyüközkan *et al*. (2008)
		Carrera and Mayorga (2008)
		Chen *et al*. (2006)
		Ren *et al*. (2007)
	linguistic terms, numerical and interval numbers	Crispim and Sousa (2005)
		Crispim and Sousa (2007)
	quantitative information: numbers and percentages	Xu *et al*. (2006)
		Xia and Wu (2007)
		Bettencourt and Rabelo (2005)
		Tang *et al*. (2006)

(*continued*)

Table 2. Continued.

Criteria	Article
	Dotoli *et al*. (2006)
	Jarimo *et al*. (2006)
	Ng (2008)
	Sari *et al*. (2007)
	Lin and Chen (2004)
	Liao and Tang (2003)
success probability, processing time, and inefficient candidate	Ip *et al*. (2003)
	Zhao *et al*. (2006a)
number of enterprises, number of redundant basic capability units, and number of basic capability units useful to the manufacturing requirement	Chen *et al*. (2007)

Due to the complexity and the nonlinearity of the model, it cannot be efficiently solved by conventional methods. With exact algorithms it is in general impossible, for large problems, to obtain a satisfactory solution in a reasonable computational time. Metaheuristics assume therefore an important role in solving these kinds of problems.

In this work, we have implemented a tabu search (TS) metaheuristic (see e.g., Glover and Laguna 1997). By a memory mechanism, TS is able to forbid certain movements during the search process, in order to diversify it. To do this, it stores the most recently accepted solutions or solution attributes (in a 'tabu list') so that solution cycling is prevented (this is one of the main competitive advantages of TS when compared with other heuristic approaches). In our problem, by repeatedly running these algorithms, it is possible for a given project, to generate a large set of solutions taking into account the different attributes (thus generating a set of 'trade-off' solutions). However, this set should also be small enough to be treatable and understandable by the DM. Moreover, it should cover the entire 'trade-off curve', i.e., it should contain solutions that represent well the different possible compromises between the attributes. Ideally we would like to have a representative set of non-dominated alternative solutions.

A solution (i.e., a potential VE configuration) is represented by a set of companies in the network, associated with the different project activities, along with the corresponding attribute values. In implementation terms, the set of initial solutions is generated through the following simple process:

- Create a *table of enterprises*, *activities and constraints* (e.g., capacities). A given activity may be performed by a group of enterprises if, for example, separately they do not have enough resources. In this case, the group of enterprises is added to the network as a single unit and the attribute values associated to this unit result from the attribute values of the different enterprises.
- By scanning that table, a candidate solution (set of enterprises) is created that optimises each criterion considered separately. This means that this initial set is composed of as many solutions as criteria.

A multi-start improvement strategy was adopted, with these initial solutions. The improvement of a solution is then done by a local search, with a neighbourhood structure that consists of swapping, for each activity, an enterprise in the current solution with an enterprise outside the solution (from the *table of enterprises*). The activities are explored in the order they have been defined in the project. In this way, the search starts by attempting to bring into the solution an alternative enterprise that can do the first activity. If this replacement leads to a non-dominated alternative, this new set of enterprises is saved in the *table of alternatives*. Then this process is repeated with the other activities. The best solution found is kept as the new current solution since the strategy used in the neighbourhood search is the 'best improvement'.

Two tabu lists are used: the first forbids the utilisation of the enterprises recently chosen, and the second forbids the choice of the last activity selected. The tabu tenure of the first tabu list is determined randomly from a given interval (in our case, [number of nodes/10; number of nodes/2]). This exploration of the neighbourhood is repeated until the search cannot reach any alternative solution (i.e., non-dominated alternative) during a constant number ξ of consecutive iterations (in our case, 5000 iterations). The search only accepts feasible solutions. An intensification strategy is adopted after a given number of consecutive dominated solutions are found, and this strategy consists of re-starting the procedure with one of the non-dominated start solutions kept.

4.1 *Multi-attribute decision-making*

4.1.1 *Linguistic approach*

There are many decision situations in which the attributes cannot be assessed precisely in a quantitative form, due to their particular nature (e.g., trust) or because either information is unavailable or the cost of their computation is too high. In these situations an 'approximate value' may be acceptable and so the use of a qualitative approach is appropriate (Herrera *et al*. 2004). 'Linguistic variables' will represent qualitative aspects, with values that are not numbers but words or sentences in a natural language, thus making it easier to express preferences. Since linguistic variables are not directly mathematically operable, to cope with this difficulty, each linguistic variable is associated with a fuzzy number characterising the meaning of each generic verbal term. *The linguistic term set*, usually called S, comprises a set of linguistic values that are generally ordered and uniformly distributed. For example, a set S of seven terms could be given as follows: $S = \{s_0 = \text{none}; s_1 = \text{very low}; s_2 = \text{low}; s_3 = \text{medium}; s_4 = \text{high}; s_5 = \text{very high}; s_6 = \text{perfect}\}$, in which $s_a < s_b$ if $a < b$. The semantics of the elements in the term set (the meaning of each term) is given by fuzzy numbers defined on the [0, 1] interval and described by membership functions.

The theory of fuzzy sets was introduced by Zadeh in 1965. It was developed to solve problems in which the descriptions of activities and observations are imprecise, vague and uncertain. A fuzzy set is a class of objects, with a continuum of membership grades that can be taken as intermediate values between 0 and 1. A fuzzy subset A of a universal set $S(x)$ is defined by a membership function $f(A(x))$ which maps each element x in $S(x)$ to a real number on [0, 1]. When the grade of membership for an element is 1, the element is considered to be absolutely in that set. When the grade of membership is 0, that element is absolutely not in the set. Ambiguous cases are assigned values between 0 and 1 (Lin *et al*. 2007). Since the linguistic assessments given by the individuals are approximate, because it may be impossible or unnecessary to obtain more accurate values, Herrera *et al*. (2002) consider that trapezoidal or triangular membership functions are good enough to capture the vagueness of those linguistic assessments. In our case we have adopted triangular membership functions because they are intuitively easy for the decision makers to use and calculate. Therefore, the membership function considered in this work is:

$$\mu_i = \begin{cases} 1 & \text{if } b_i = x \\ 0 & \text{if } x \notin \text{to term label} \\ \dfrac{x - a_{\mathrm{i}}}{b_i - a_i} & \text{if } a_i \leq x \leq b_i \\ \dfrac{c_i - x}{c_i - b_i} & \text{if } b_i \leq x \leq c_i \end{cases} . \quad (12)$$

In our work, we accept different types of variables: numerical, interval, and linguistic and, in the case of linguistic variables, we also accept different cardinalities for S, and different semantics in the term set, depending on the DM and/or the attribute in question. This becomes an advantage as it allows the DM to be more or less detailed, when dealing with different attributes.

4.1.2 *Fuzzy TOPSIS procedure*

TOPSIS is one classical multi-criteria decision-making method, developed by Hwang and Yoon (1981). Based on the idea that the chosen alternative should be as ‘close’ as possible to the positive ideal solution and, on the other hand, as ‘far’ as possible from the negative ideal solution (see Figure 2), the method is very easy to implement. However, it assumes the satisfaction of the following requirements: a previous assignment of weights to the attributes by the DM, and a fixed, pre-defined number of alternatives (Shih *et al.* 2004).

Fuzziness is inherent to most decision making processes when linguistic variables are used to describe qualitative data. In this context, we will use an extension of the TOPSIS procedure for fuzzy data based on the following steps:

Step 1: Identify the evaluation criteria.

Step 2: Generate the alternatives.

Step 3: Evaluate alternatives in terms of the criteria (i.e., compute the fuzzy values of the criterion functions).

Step 4: Identify the weights of the criteria.

Step 5: Construct the fuzzy decision matrix.

Step 6: Compute the normalised fuzzy decision matrix.

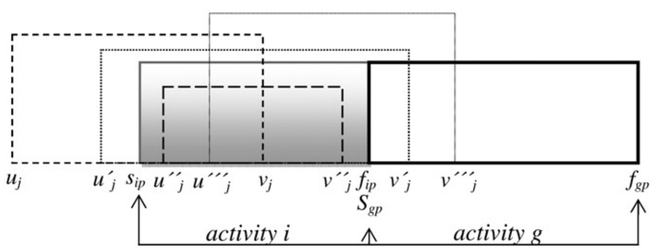

Figure 2. Time window constraint with several hypotheses.

Step 7: Construct the weighted normalised fuzzy decision matrix.

Step 8: Identify a fuzzy positive ideal solution and a fuzzy negative ideal solution.

Step 9: Compute the distance between each alternative i and the fuzzy positive ideal solution (Equation 13) and between each alternative i and the fuzzy negative ideal solution (Equation 14).

Step 10: Compute the 'closeness coefficient' to determine the ranking order of all alternatives (Equation 15):

$$d_i^+ = \sum_{j=1}^{N} d(v_{ij}, v_{ij}^+), \quad i \in M \tag{13}$$

$$d_i^- = \sum_{j=1}^{N} d(v_{ij}, v_{ij}^-), \quad i \in M \tag{14}$$

where N is the total number of alternatives and M the set of criteria and $v_{ij}^+ = (1, 1, 1)$ is the fuzzy positive ideal solution and $v_{ij}^- = (0, 0, 0)$ is the fuzzy negative ideal solution for each criterion (benefit or cost criterion).

$$R_i = \frac{d_i^-}{(d_i^+ + d_i^-)}, \quad i \in M \tag{15}$$

Our approach presents some differences to the standard procedure namely:

(1) To construct the fuzzy decision matrix we first need to transform the numerical values, interval values and linguistic terms into fuzzy sets (see Herrera *et al.* 2004) by using Equation (12). Due to the incommensurability among attributes, to do this transformation we previously need to normalise the values of the attributes (thus not requiring to do step 6 above). The most commonly used normalisation method is as follows (Wang and Parkanc 2006):

$$z_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}, \quad i = 1, \ldots, n, \ j \in \Omega_1 \tag{16}$$

$$z_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}, \quad i = 1, \ldots, n, \ j \in \Omega_2, \tag{17}$$

where $X = n \times m$ is a decision matrix, z_{ij} are the normalised attribute values, $x_j^{\min} = \min_{1 \le i \le n}\{x_{ij}\}$, $x_j^{\max} = \max_{1 \le i \le n}\{x_{ij}\}$, and the sets Ω_1 and Ω_2 are, respectively, the sets of benefit attributes and cost attributes.

(2) Since each solution involves a given number of companies for the same project activities, and to evaluate that solution we take the values of each attribute considered for each company separately, we may need to use an aggregation mechanism to evaluate each potential VE configuration. This obviously leads to some loss of information. To avoid it we consider some artificial attributes that characterise the solution itself. In this way, for a given project with I activities and

a network of enterprises characterised by M attributes, the solution includes the enterprises that will perform the I activities ($M \times I$ attributes). Following this principle we do not need to perform any aggregation and we keep all the information of all enterprises in the solution.

(3) Instead of using fuzzy numbers in the fuzzy decision matrix we use fuzzy sets since we want to give more autonomy to the DM (through the use of different and more extensive cardinality ranges in linguistic attributes). Therefore, we use distance formulas for membership functions (see Balopoulos *et al.* 2007). For any two fuzzy sets A, $B \in f(S(X))$, with membership functions μ and ν, respectively, we use the following normalised Euclidean distance:

$$d_{nE}(\mu, \nu) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mu(x_i) - \nu(x_i))^2}. \quad (18)$$

4.1.3 *Sensitivity analysis*

Sensitivity analysis adequately reflects the final DM's assessments about the criteria importance, since they are determined subjectively. In the example below, the weights are given in terms of a percentage, but it is possible that the DM uses linguistic terms to express the criteria importance. The DM certainly wishes to identify the impact of changes in the weight coefficients on the ranking order obtained. This analysis is made by changing each weight criterion, maintaining the others constant, i.e., with the same proportionality, in order to obtain stability intervals for each criterion.

5. Illustrative example

Assume we would like to form a VE to perform two projects decomposed into six activities each (Table 3). Project 1 can start immediately and has to be completed before day 165. Project 2 can start on day 10 and has to be completed before day 234. Data is such that projects can be performed simultaneously, and one company or group of companies are able to perform more than one activity in a project, or to perform activities in both projects.

Consider a network where 12 different activities that require 10 different resources can be performed. The network is composed of 100 companies characterised by: company code (number in the interval [1–100]; activity; interval time for the availability of resources; capacity; and eight evaluation attributes (Table 4). The attribute types may be: linguistic, numerical and interval. We may want to maximise the attribute (benefit criteria) or minimise it (cost criteria). If the attribute is linguistic, the scale cardinality has to be defined $(3, 5, 7)$. Figures have been randomly generated. The duration of activities is also randomly defined in the interval $[30, 100]$, the *earliest start time* randomly defined in the interval $[0, 365 - \text{duration}]$, the *latest finish time* randomly defined in the interval [earliest start time, 365] and the *quantity of resources* randomly defined in the interval $[100, 1000]$.

Figure 5 presents the precedence diagram of each project, and Figure 6 presents a Gantt chart of the resources showing possible conflicts between the activities.

Table 3. Projects data.

Project 1							Project 2						
Activities (code)	Resources	Precedent activities	Duration	Earliest start time	Latest finish time	Quantity of resources	Activities (code)	Resources	Precedent activities	Duration	Earliest start time	Latest finish time	Quantity of resources
A	7	–	36	0	106	400	G	4	–	99	10	159	362
B	8	–	62	0	97	604	H	2	–	56	10	202	206
C	3	–	67	0	122	528	I	9	–	30	10	202	135
D	5	A	16	36	122	275	J	6	G	41	109	202	116
E	4	B	25	62	122	368	L	8	G	44	109	202	221
F	8	C,E,D	43	87	165	304	K	9	H,I,L,J	32	153	234	282

Table 4. Description of attributes.

Attributes (objectives)	$c1$	$c2$	$c3$	$c4$	$c5$	$c6$	$c7$	$c8$
Example	Attitude toward uncertainty/risk	Productivity	Price (per unit)	Production capacity	Market entrance capability	Partnership experience	Cost (per unit)	Technical expertise
Type	linguistic	numerical	interval	interval	linguistic	numerical	numerical	linguistic
Max (+)/min (−)	+	+	−	−	+	+	−	+
Cardinality (for linguistic)	7	–	–	–	3	–	–	7
Weight (%)	20	23	2	7	19	13	14	2

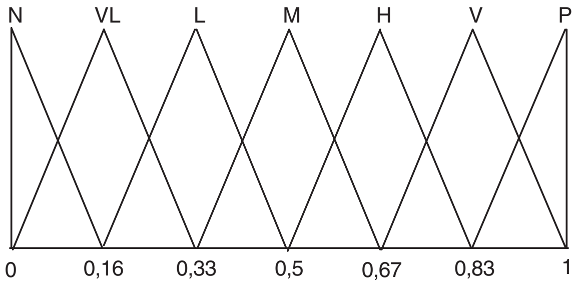

Figure 3. A set of seven terms.

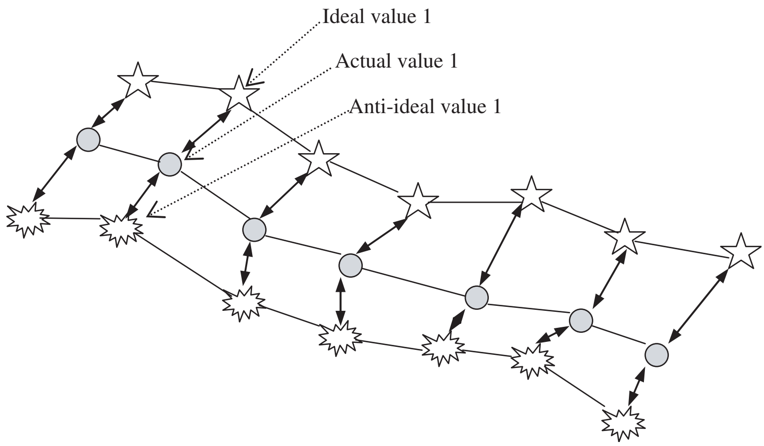

Figure 4. TOPSIS.

We can notice that there are conflicts between activities concerning the use of the same resource, for example, activities D and G require resource 8 at the same time. To avoid these situations and to ensure that a feasible solution is obtained, we allow the existence of some slack, for each activity. By applying the tabu search procedure we have obtained 10 non-dominated alternatives as shown in Table 5. In this table, each row contains the VE composition for the project activities (i.e., the companies assigned to the activities). For example, solution VE1 for project 1 includes companies 83, 81, 48, 68, 39 and 81, respectively for activities 1, 2, 3, 4, 5 and 6.

5.1 *Fuzzy TOPSIS approach*

Following, the inputs have been fuzzified, according to their own membership function and linguistic variables terms set, without performing any type of aggregation. An example of the fuzzy sets employed can be seen in Table 6 for project 1, non-dominated alternative 1 and criterion 7 (cost per unit). The calculations for project 1, non-dominated alternative 1, activity 2, criterion 7 and cardinality 4 (corresponding to M in Figure 1) to determine the correspondent element of the fuzzy set are: $0.14370811 = (0.67 - 0.64557)/(0.670 - 0.5)$,

Table 5. Non-dominated alternatives.

Project 1 activities							Project 2 activities						
	1	2	3	4	5	6		1	2	3	4	5	6
VE1	83	81	48	68	39	81	VE1	39	10	27	17	27	81
VE2	35	22	41	79	75	22	VE2	75	59	27	4	27	22
VE3	21	97	14	26	75	97	VE3	75	59	109	86	109	97
VE4	21	81	14	13	102	81	VE4	77	36	25	51	25	81
VE5	35	71	30	31	47	71	VE5	57	2	110	4	110	71
VE6	74	44	48	55	57	44	VE6	57	2	110	34	110	44
VE7	42	44	41	79	39	44	VE7	39	98	27	56	27	44
VE8	7	44	30	13	75	44	VE8	75	80	110	17	110	44
VE9	100	97	48	90	104	97	VE9	108	98	110	99	110	97
VE10	21	44	41	79	39	44	VE10	39	33	27	56	27	44

Table 6. Example of fuzzy sets.

Fuzzy sets for project 0, 1st alternative, criterion 7 – partnership experience											
#	Activity 1	#	Activity 2	#	Activity 3	#	Activity 4	#	Activity 5	#	Activity 6
[1]	0.00000000	[1]	0.00000000	[1]	0.00000000	[1]	0.00000000	[1]	0.00000000	[1]	0.00000000
[2]	0.00000000	[2]	0.00000000	[2]	0.00000000	[2]	0.00000000	[2]	0.00000000	[2]	0.00000000
[3]	0.00000000	[3]	0.00000000	[3]	0.54901963	[3]	0.00000000	[3]	0.00000000	[3]	0.00000000
[4]	0.00000000	[4]	0.14370811	[4]	0.45098040	[4]	0.00000000	[4]	0.00000000	[4]	0.14370811
[5]	0.00000000	[5]	0.85629189	[5]	0.00000000	[5]	0.086925283	[5]	0.00000000	[5]	0.85629189
[6]	0.37151715	[6]	0.00000000	[6]	0.00000000	[6]	0.91307473	[6]	0.00000000	[6]	0.00000000
[7]	0.62848282	[7]	0.00000000	[7]	0.00000000	[7]	0.00000000	[7]	1	[7]	0.00000000

with 0.64557 being the normalised value obtained through $(218-116)/(218-60)$ where 218 and 60 are the maximum and minimum values for that criteria in the original data, respectively, and 116 is the original value for the alternative 1, activity 2 in respect to criterion 7.

Afterwards, we calculated the ranking of the non-dominated alternatives set, shown in Table 7, through the computation of the distances between each alternative and the fuzzy set positive and negative ideal solutions, as well as the 'closeness coefficients'. Only at this stage, do we make an aggregation of information, in order to show the results to the DM in an understandable way. Otherwise, the DM was forced to analyse which would be the best alternative for each criterion, which could be tedious and difficult. Moreover, in spite of the fact that, in our example, the best alternative has the shortest distance to d+ and the highest distance to d−, that may not be the case and then it would be even more difficult for the DM to chose one alternative (one example of this issue can be found in Crispim and Sousa (2005, p. 152: Table 4).

Analysing the results obtained from the two ranking approaches, we would recommend for project 1, VE_4, clearly better (0.05128) than VE_3, in the second position with 0.04535; and for project 2, VE_3.

5.2 *Sensitivity analysis*

The stability intervals of each criterion, see Figure 7, show the intervals where the first position of the ranking previously obtained (Table 6) remains unaffected. For example (Figure 7), in project 1 the weight of the first criterion can change between [−1%, 23%] without affecting the winning VE configuration (VE_4).

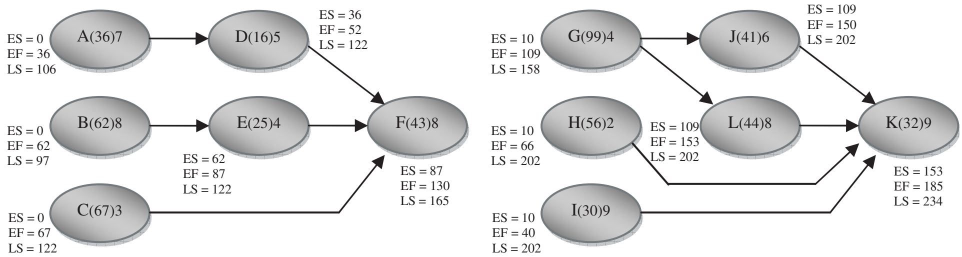

Figure 5. Sequence graphs for projects 1 and 2.

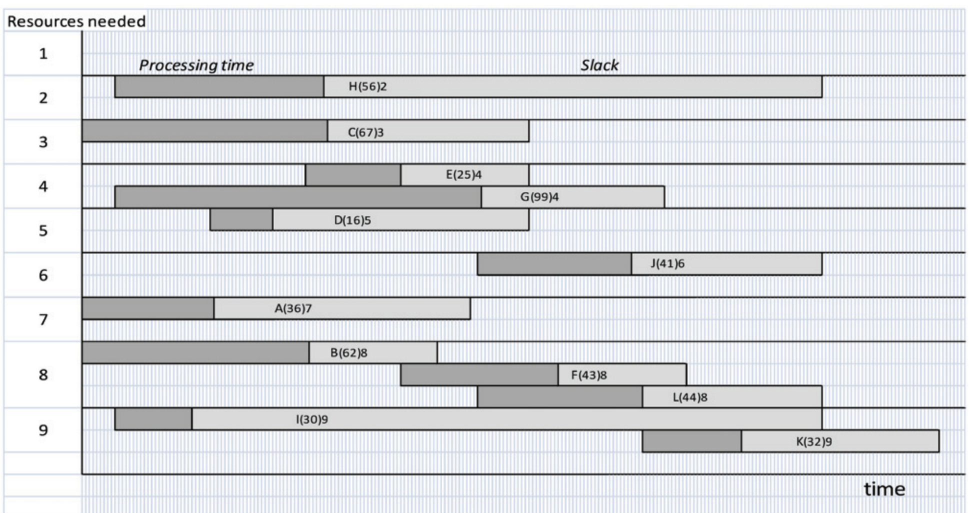

Figure 6. Gantt chart of projects 1 and 2.

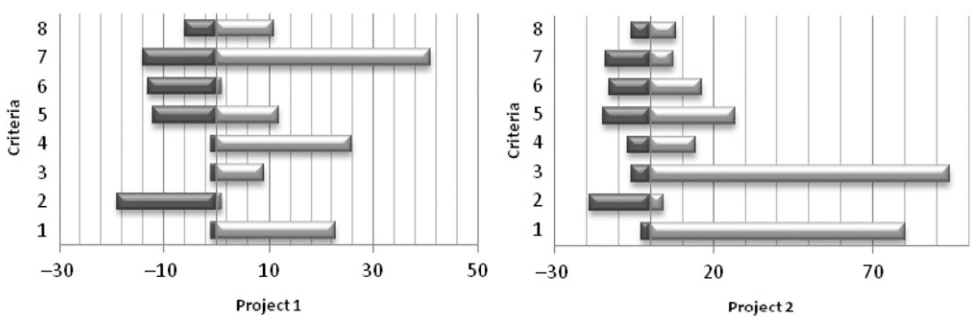

Figure 7. Projects 1 and 2 – stability interval.

6. Conclusions

Partner selection in a VE is a critical process and consists of choosing the entities to be involved in an emergent business opportunity, according to their attributes and interactions. The work presented in this paper is in line with the key trends we have identified in a comprehensive literature survey, by namely considering: a) multiple attributes to describe/structure the decision problem; b) different types of 'variables' in order to facilitate the expression of the preferences of the decision-maker; c) the subjectivity of information that leads to the use of a 'fuzzy' approach; d) an optimisation perspective through the use of metaheuristics; and e) the dynamic aspects occurring when various projects take place simultaneously.

The purpose of this study was to develop an easy-to-use and flexible multi-period decision support system for the partner selection problem. The development of dynamic (multi-period) and flexible approaches is very important in the VE research area because of the temporary distinctive nature of this type of collaboration. The flexibility of the approach arises from the possibility of choosing different objectives and constraints for each project, and from the variety of variable types that the DMs can use to express their preferences. This way, the main managerial implication of this work is to provide a generalised research framework that can be used to analyse and structure many partner selection situations.

The proposed approach presented a hybrid algorithm that used for the first time in this domain (to the best of our knowledge), a multi-objective multi-period metaheuristic combined with the TOPSIS technique in a fuzzy environment, to search and rank potential VE configurations.

This work can also be of great relevance in the professional virtual communities context, namely in *research and development projects* where coordinators try to find a group of people with different skills and capacities for performing some specific research activities.

Our conclusions may have been partially affected by the fact that we have gathered simulated data. In future research we will therefore need to apply real world data and improve the approach to cope with situations where the product or service to be delivered is not known or structured in advance.

Table 7. Closeness coefficients/ranking of the alternatives.

Project 1					Project 2				
Rank	VE	$\tilde{d}_i^+$	$\tilde{d}_i^-$	$\tilde{R}_i$	Rank	VE	$\tilde{d}_i^+$	$\tilde{d}_i^-$	$\tilde{R}_i$
1	4	306.394	16.5643	0.05128	1	3	307.100	15.2357	0.04726
2	3	307.585	14.6141	0.04535	2	2	308.035	14.9483	0.04628
3	1	308.198	14.5867	0.04519	3	1	308.248	14.3540	0.04449
4	8	307.644	14.5391	0.04512	4	7	308.392	14.2846	0.04426
5	9	307.804	14.5092	0.04501	5	4	308.263	14.1921	0.04401
6	2	307.913	13.9505	0.04334	6	5	308.451	13.8885	0.04308
7	7	308.742	13.0287	0.04049	7	0	308.835	12.9139	0.04013
8	0	308.631	12.9402	0.04024	8	6	308.952	12.5320	0.03898
9	5	308.548	12.8897	0.04010	9	9	308.841	12.4384	0.03871
10	6	309.021	12.8263	0.03985	10	8	309.093	12.2121	0.03800

References

Araz, C., Ozfirat, M.P., and Ozkarahan, I., 2007. An integrated multicriteria decision-making methodology for outsourcing management. *Computers & Operations Research*, 34 (12), 3738–3756.

Balopoulos, V., Hatzimichailidis, A.G., and Papadopoulos, B.K., 2007. Distance and similarity measures for fuzzy operators. *Information Sciences*, 117 (11), 2336–2348.

Bettencourt, F. and Rabelo, R.J., 2005. A systematic approach for VE partners selection using the SCOR model and the AHP method. *In*: L.M. Camarinha-Matos, H. Afsarmanesh and A. Ortiz, eds. *Collaborative networks and their breeding environments. Series: IFIP International Federation for Information Processing*, Volume 224. Boston, MA: Springer, 99–108.

Büyüközkan, G., Feyzioglu, O., and Nebol, E., 2008. Selection of the strategic alliance partner in logistics value chain. *International Journal of Production Economics*, 113 (1), 148–158.

Camarinha-Matos, L.M. and Afsarmanesh, H., 2003. Elements of a base VE infrastructure. *Computers in Industry*, 51 (51), 139–163.

Cao, H. and Gao, Y., 2006. Penalty guided genetic algorithm for partner selection problem in agile manufacturing environment. *In*: *Intelligent control and automation, WCICA 2006*, Volume 1, 21–23 June, Dalian, China, 3276–3280.

Cao, J., *et al*., 2004. A new method for VE partner selection and evaluation based on AHP and fuzzy theory. *In*: *The 8th international conference on computer supported cooperative work in design*, Volume 2, 26–28 May, Xiamen, China, 563–566.

Cao, J. and Zhou, G., 2006. Partner selection and evaluation in agile virtual enterprise based upon TFN-AHP model. *In*: *The 10th international conference on computer supported cooperative work in design*, 3–5 May, Nanjing, China, 1–6.

Cao, J., Ye, F., and Zhou, G., 2006. A new web-based method for partner selection in the agile virtual enterprise. *In*: *The sixth world congress on intelligent control and automation, WCICA 2006*, Volume 2, 21–23 June, Dalian, China, 6920–6924.

Carrera, D.A. and Mayorga, R.V., 2008. Supply chain management: a modular fuzzy inference system approach in supplier selection for new product development. *Journal of Intelligent Manufacturing*, 19 (1), 1–12.

Chen, C.-T., Lin, C.-T., and Huang, S.-F., 2006. A fuzzy approach for supplier evaluation and selection in supply chain management. *International Journal of Production Economics*, 102 (2), 289–301.

Chen, Q.X., Chen, X., and Lee, W.B., 2007. Qualitative search algorithms for partner selection and task allocation in the formulation of virtual enterprise. *International Journal of Computer Integrated Manufacturing*, 2 (20), 115–126.

Crispim, J. and Sousa, J.P., 2005. A multi-criteria decision support system for the formation of collaborative networks of enterprises. *In*: L.M. Camarinha-Matos, H. Afsarmanesh and A. Ortiz, eds. *Collaborative networks and their breeding environments. Series: IFIP International Federation for Information Processing*, Volume 224. Boston, MA: Springer, 143–154.

Crispim, J. and Sousa, J.P., 2007. Multiple criteria partner selection in virtual enterprises. *In*: L.M. Camarinha-Matos, H. Afsarmanesh, P. Novais, and C. Analide, eds. *Establishing the foundation of collaborative networks. Series: IFIP International Federation for Information Processing*, Volume 243. Boston, MA, Springer, 197–206.

Dai, C. and Yang, Y., 2005. The method integration model for partner selection in the virtual enterprise. *In*: *Proceedings of international conference ICSSSM '05 on services systems and services management*. Volume 1, 13–15 June, Chongquing, China, 716–720.

Ding, H., Benyoucef, L., and Xie, X., 2006. A simulation-based multi-objective genetic algorithm approach for networked enterprises optimisation. *Engineering Applications of Artificial Intelligence*, 19 (6), 609–623.

Dotoli, M., *et al.*, 2005. A multi-level approach for network design of integrated supply chains. *International Journal of Production Research*, 43 (20), 4267–4287.

Dotoli, M., *et al.*, 2006. Design and optimisation of integrated E-supply chain for agile and environmentally conscious manufacturing. *IEEE Transactions on Systems, Man, and Cybernetics—Part A: Systems and Humans*, 36 (1), 62–75.

Gao, F., *et al.*, 2006. Application of improved discrete particle swarm algorithm in partner selection of virtual enterprise. *IJCSNS International Journal of Computer Science and Network Security*, 6 (3A), 208–212.

Gaonkar, R. and Viswanadham, N., 2004. A conceptual and analytical framework for the management of risk in supply chains. *In*: *IEEE international conference on robotics and automation*, *ICRA '04*, Volume 3, 26 April–1 May, Barcelona, Spain, 2699–2704.

Glover, F. and Laguna, M., 1997. *Tabu search*. Boston, MA: Kluwer Academic Publishers.

Hajidimitriou, Y.A. and Georgiou, A.C., 2002. A goal programming model for partner selection decisions in international joint ventures. *European Journal of Operational Research*, 138 (3), 649–662.

Heavy, C., *et al.*, 2006. Operational design in VO supply networks creation. *In*: L.M. Camarinha-Matos, H. Afsarmanesh, and M. Ollus, eds. *Network-centric collaboration and supporting frameworks*. *Series: IFIP International Federation for Information Processing*, Volume 224. Boston, MA: Springer, 381–388.

Herrera, F., Lopez, E., and Rodriguez, M.A., 2002. A linguistic decision model for promotion mix management solved with genetic algorithms. *Fuzzy Sets and Systems*, 131 (1), 47–61.

Herrera, F., Martiınez, L., and Sanchez, P.J., 2004. Decision aiding managing non-homogeneous information in group decision making. *European Journal of Operational Research*, 166 (1), 115–132.

Ho, G.T.S., *et al.*, 2006. A hybrid intelligent system to enhance logistics workflow: an OLAP-based GA approach. *International Journal of Computer Integrated Manufacturing*, 19 (1), 69–78.

Huang, H. and Chen, J., 2005. A partner selection method based on risk evaluation in virtual enterprises. *In*: *International conference on services systems and services management*, *ICSSSM '05*, Volume 1, 13–15 June, Chongquing, China, 608–612.

Huang, X., Wong, Y., and Wang, J., 2004. A two-stage manufacturing partner selection framework for virtual enterprises. *International Journal of Computer Integrated Manufacturing*, 17 (4), 294–304.

Huang, X.G., *et al.*, 2005. Critical-path-analysis-based dynamic component supplier optimisation. *International Journal of Computer Integrated Manufacturing*, 18 (8), 702–709.

Hwang, C.L. and Yoon, K. 1981. Multiple attribute decision making: methods and applications. Berlin: Springer.

Ip, W.H., *et al.*, 2003. Genetic algorithm solution for a risk-based partner selection problem in a virtual enterprise. *Computers and Operations Research*, 30 (2), 213–231.

Ip, W.H., Yung, K.L., and Wang, D., 2004. A branch and bound algorithm for sub-contractor selection in agile manufacturing environment. *International Journal of Production Economics*, 87 (2), 195–205.

Jarimo, T. and Pulkkinen, U., 2005. A multi-criteria mathematical programming model for agile virtual organiztion creation. *In*: L.M. Camarinha-Matos, H. Afsarmanesh and A. Ortiz, eds. *Collaborative networks and their breeding environments*. *Series: IFIP International Federation for Information Processing*, Volume 224. Boston, MA: Springer, 127–142.

Jarimo, T., Salkari, I., and Bollhalter, S., 2006. Partner selection with network interdependencies: an application. *In*: L.M. Camarinha-Matos, H. Afsarmanesh and M. Ollus, eds. *Network-centric collaboration and supporting frameworks*. *Series: IFIP International Federation for Information Processing*, Volume 224. Boston, MA: Springer, 389–396.

Kahraman, C., Cebeci, U., and Ulukan, Z., 2003. Multi-criteria supplier selection using fuzzy AHP. *Logistics Information Management*, 16 (6), 382–394.

Kang, K., Zhang, J., and Xu, B., 2007. Optimising the selection of partners in collaborative operation networks in advanced intelligent computing theories and applications with aspects of artificial intelligence. *Lecture Notes in Computer Science*, 4682, 836–850.

Kim, T.-Y., *et al.*, 2006. A modeling framework for agile and interoperable virtual enterprises. *Computers in Industry*, 57 (3), 204–217.

Ko, C.S., Kim, T., and Hwang, H., 2001. External partner selection using tabu search heuristics in distributed manufacturing. *International Journal of Production Research*, 39 (17), 3959–3974.

Li, Y. and Liao, X., 2007. Decision support for risk analysis on dynamic alliance. *Decision Support Systems*, 42 (4), 2043–2059.

Liao, X.-W. and Tang, H.-W., 2003. An evidential reasoning approach for partner selection in dynamic alliance. *Computer Integrated Manufacturing System (China)*, 9 (1), 57–62.

Lin, C.-W.R. and Chen, H.-Y.S., 2004. A fuzzy strategic alliance selection framework for supply chain partnering under limited evaluation resources. *Computers in Industry*, 55 (2), 159–179.

Lin, H.-Y., Hsu, P.-Y., and Sheen, G.-J., 2007. A fuzzy-based decision-making procedure for data warehouse system selection. *Expert Systems with Applications*, 32 (3), 939–953.

Ma, X., *et al.*, Y., 2007. An improved adaptive genetic algorithm in optimisation of partner selection. *In*: *Eighth ACIS international conference on software engineering, artificial intelligence, networking, and parallel/distributed computing, SNPD 2007*, Volume 3, 30 July–1 August, Qingdao, China 455–460.

Mikhailov, L., 2002. Fuzzy analytical approach to partnership selection in formation of virtual enterprise. *Omega*, 30 (5), 393–401.

Ng, W.L., 2008. An efficient and simple model for multiple criteria supplier selection problem. *European Journal of Operational Research*, 186 (3), 1059–1067.

Ren, F., Zhang, M., and Bai, Q., 2007. A fuzzy-based approach for partner selection in multi-agent systems. *In*: *6th IEEE/ACIS international conference on computer and information science*, *ICIS 2007*, 11–13 July, Melbourne, Australia, 457–462.

Sari, B., Sen, T., and Kilic, S.E., 2007. AHP model for the selection of partner companies in virtual enterprises. *International Journal of Advance Manufacturing Technology*, DOI 10.1007/s00170-007-1097-6.

Sha, D.Y. and Che, Z.H., 2005. Virtual integration with a multi-criteria partner selection model for the multi-echelon manufacturing system. *International Journal of Advanced Manufacturing Technology*, 25 (7–8), 793–802.

Sha, D.Y and Che, Z.H., 2006. Supply chain network design: partner selection and production/distribution planning using a systematic model. *Journal of Operational Research Society*, 57 (1), 52–62.

Shih, H.-S., Wang, C.-H., and Lee, E.S., 2004. A multiattribute GDSS for aiding problem-solving. *Mathematical and Computer Modelling*, 39 (11–12), 1397–1412.

Tang, Q., Fang, X., and Xiang-Bo, L., 2006. Multiobject decision-making model for virtual enterprise partners selection. *In*: *International conference on machine learning and cybernetics*, 13–16 August, Dalian, China, 1790–1795.

Viswanadham, N. and Gaonkar, R.S., 2003. Partner selection and synchronised planning in dynamic manufacturing networks. *IEEE Transactions on Robotics and Automation*, 19 (1), 117–130.

Wang, D., Yung, K.L., and Ip, W.H., 2001. A heuristic genetic algorithm for subcontractor selection in a global manufacturing environment. *IEEE Transactions on Systems, Man, and Cybernetics—Part C: Applications and Reviews*, 31 (2), 189–198.

Wang, J. and Lin, H.-Y., 2006. A fuzzy hybrid decision-aid model for selecting partners in the design chain. *International Journal of Production Research*, 44 (10), 2047–2069.

Wang, T.-C. and Chen, Y.-H., 2007. Applying consistent fuzzy preference relations to partnership selection. *Omega*, 35 (4), 384–388.

Wang, Y.-M. and Parkanc, C., 2006. A general multiple attribute decision-making approach for integrating subjective preferences and objective information. *Fuzzy Sets and Systems*, 157 (10), 1333–1345.

Wu, N. and Su, P., 2005. Selection of partners in virtual enterprise paradigm. *Robotics and Computer-Integrated Manufacturing*, 21 (2), 119–131.

Xia, W. and Wu, Z., 2007. Supplier selection with multiple criteria in volume discount environments. *Omega*, 35 (5), 494–504.

Xu, S., *et al.*, 2006. Research on virtual logistic enterprises partners selection method based on CLIQUE. *In*: *10th international conference on computer supported cooperative work in design*, 3–5 May, Nanjing, China, 1–5.

Ye, F. and Li, Y., 2005. Multi-attribute decision-making model for virtual enterprise partners selection under uncertain information condition. *In*: *International conference on services systems and services management*, *ICSSSM '05*, Volume 2, 13–15 June, Chongquing, China, 1162–1165.

Zeng, Z., *et al.*, 2005. A new algorithm for partner selection in virtual enterprise. *In*: *Sixth international conference on parallel and distributed computing*, *applications and technologies*, *PDCAT 2005*, 05–08 December, Dalian, China, 884–886.

Zhao, F., Hong, Y., and Dongmei, W., 2004. A novel genetic algorithm for partner selection problem in virtual enterprise. *In*: *Proceedings of the 2004 international conference on intelligent mechatronics and automation chengdu*, 26–31 August, Chengdu, China, 477–482.

Zhao, F., Hong, Y., and Dongmei, W., 2006a. A multi-objective optimisation model of the partner selection problem in a virtual enterprise and its solution with genetic algorithms. *International Journal of Advanced Manufacturing Technology*, 28 (11–12), 1246–1253.

Zhao, F-Q, Zhang, Q.-Y., and Yang, Y-H., 2006b. A hybrid self-adaptive PSO algorithm and its applications for partner selection in holonic manufacturing system (HMS). *In*: *International conference on machine learning and cybernetics*, 13–16 August, Dalian, China, 2536–2541.

Zhao, H., *et al.*, 2006c. A novel partner selection algorithm based on GA and fussy decision-making in manufacturing extended enterprise. *In*: *The sixth world congress on intelligent control and automation*, *WCICA* 2006, Volume 2, 21–23 June, Dalian, China, 6934–6938.

Yang, C., Xue, H., and Ding, J., 2006. An adaptive genetic algorithm for selecting partners in virtual enterprise. *In*: *The sixth world congress on intelligent control and automation*, *WCICA* 2006, *volume* 2, 21–23 June, Dalian, China, 6826–6830.