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Chong Wu and David Barnes

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A Four-phase Conceptual Model for Supplier Selection in Agile Supply Chains

Chong Wu, Business School, Central South University, Changsha, 410083 P.R. China

Email: chong.wu@rhul.ac.uk

* David Barnes, School of Management, Royal Holloway, University of London
Egham, Surrey TW20 0EX, United Kingdom

Email: david.barnes@rhul.ac.uk

* Corresponding author

Abstract

A four-phase conceptual model for supplier selection in agile supply chains (ASCs) is presented. The use of ASCs has become more common in today's increasingly dynamic markets. However, supplier selection decisions are inherently more complex and difficult under the conditions of uncertainty and ambiguity created as supply chains form and re-form. The four phases of the model comprise Supplier selection preparation, Pre-classification, Final selection and Application feedback. It draws on a range of quantitative and qualitative techniques. These include application of the Dempster-Shafer and optimisation theories, radial basis function artificial neural networks (RBF-ANN), analytic network process-mixed integer multi-objective programming (ANP-MIMOP), Kraljic's supplier classification matrix and the principles of continuous improvement. The resulting model offers a comprehensive and systematic approach to tackling this increasingly important task.

Keywords: Agile supply chain; supplier selection; conceptual model; artificial neutral network; analytical network process; multi-objective programming

A Four-phase Conceptual Model for Supplier Selection in Agile Supply Chains

CHONG WU, Business School, Central South University, Changsha, P.R. China

DAVID BARNES, School of Management, Royal Holloway, University of London

INTRODUCTION

Selecting the suppliers from which an organization should obtain the resources it needs for its operations has long been considered a key management task (Dickson, 1966; Kraljic, 1983; Weber et al., 1991; Choi and Hartley, 1996; De Boer et al., 2001; Sarkar and Mohapatra, 2006). Indeed, some consider it to be the most important of all the responsibilities of the purchasing and supply function, as the choice of supplier has a significant impact on the quality, quantity, timeliness and price of purchased goods and services (Dulmin and Mininno, 2003; Sarkis et al., 2007). Furthermore, suppliers can also have a direct and significant impact on the quality, cost and lead time of the new products and technologies needed to meet new market demands (Vokurka and Fliedner, 1998; Meade and Sarkis, 1999; Humphreys et al., 2007).

Supplier selection is, however, a complex problem as it is multi-objective in nature. In what is now considered classic research, Dickson (1966) identified 23 criteria that might be applied in supplier selection decision-making. Subsequent researchers have sought to modify the number and relative importance of these criteria in the light of the changing business environment (e.g. Dempsey, 1978). In the intervening years, the business environment has become more complex and dynamic (Hakansson and Snehota, 2006). Although there is broad agreement that supplier selection criteria should relate to operational performance and competitive priorities such as cost, quality, delivery and flexibility (De Meyer et al., 1989; Verma and Pullman, 1998; Vonderembse and Tracey, 1999; Chen and Lin, 2006), increasingly demanding business conditions point to the need for a wider range of criteria (Yusuf et al., 1999; Cagliano et al., 2004; Ngai et al., 2004). Also, under dynamic conditions, supplier selection criteria are likely to need to change over time (Sarkis, 2007; Baker, 2008). Thus, the task of supplier selection has, arguably become increasingly important as it has become more complex (Choi and Hartley, 1996; De Boer et al., 2001; Sarkar and Mohapatra, 2006). In these increasingly turbulent and dynamic conditions, which have increased uncertainty and ambiguity in the supplier decision making process, the response of many firms has been to adopt the concept of the agile supply chain (Christopher, 2000; Christopher and Towill, 2000).

An agile supply chain (ASC) is a dynamic alliance of member companies, the formation of which is likely to need to change frequently, forming and re-forming in response to fast-changing market conditions. The successful operation of an ASC depends upon an ability to select the most appropriate suppliers in any given situation. If the supplier selection process is to be conducted in as comprehensive and thorough manner as possible, many aspects of the performance of potential suppliers will need to be assessed. This implies that large quantities of data about potential suppliers will need to be collected and analysed. Because, in an ASC, the requirements for suppliers may change over time, supplier selection becomes a more frequent task. A further complication arises in that the performance of potential suppliers will need to be assessed against different criteria at different times. Furthermore, different potential suppliers may have different characteristics with regard to different performance criteria (Xia and Wu, 2007). Also, the globalization of world trade is providing purchasers with increased opportunities for sourcing goods and services in foreign countries. This not only increases the number of potential suppliers to consider but makes the task of collecting and analysing data about them more challenging. In summary, supplier selection in ASCs presents a significant information processing challenge. It might therefore be expected that purchasing and supply managers would look to use quantitative methods to underpin their supplier selection decision-making.

More importantly, many decision support models emphasize the final stages of the supplier selection process only, when, typically a choice has to be made between a small number of shortlisted suppliers (e.g. Weber et al., 1991, 1993; Dulmin and Mininno, 2003). However, it is important not to neglect the early stages of the process as the quality of decision-making at the final choice stage is largely dependent on decisions already made in the previous stages (De Boer and Van der Wegen, 2003). Secondly, existing methods pay little attention to the task of selecting new suppliers (De Boer et al., 2001), which can be particularly important in ASCs. Thus, in practice many managers often rely on qualitative methods and subjective judgements when tackling the problem of supplier selection (Gencer and Gurpinar, 2007). This is a pity because recent advances in computer programming can offer decision-makers the processing power necessary to conduct the level of information processing required for effective quantitative analysis. In particular, techniques such as artificial neural networks (ANN), especially radial basis function artificial neural networks (RBF-ANN), and analytic network process-mixed integer multi-objective programming (ANP-MIMOP) appear to have the potential to help in supplier selection. Yet, few researchers in this field have tried to apply such techniques.

Although there is a wealth of literature on specific aspects of supplier selection, very little attention has been given to modelling the entire process of the supplier selection decision-making process in ASCs. De Boer et al. (2001) have characterized supplier selection as a multi-stage process. However, their approach makes extensive use of managerial subjective judgement. On the other hand, Lin and Chen (2004) take a more quantitative approach, in developing a fuzzy decision-making framework for supplier selection. The principle underlying their approach is that of formulating a set of optimal criteria for supplier selection based on the distinctive features of the industry from which the supplier as to be selected. This not only enables best use to be made of valuable evaluation resources, but also increases the chances of selecting the best potential supplier.

This paper builds on these contributions by presenting a four phase model for supplier selection in ASCs. The model incorporates modern computer programming techniques to overcome the information processing difficulties inherent in selecting suitable suppliers from amongst large numbers of potential suppliers against multiple criteria in conditions of uncertainty. In so doing, it aims to offer a comprehensive and rigorous approach whilst avoiding unnecessary complexity in order to make it accessible to practicing managers.

Following this introductory discussion, the paper is structured as follows. The rationale for a four phase conceptual model for supplier selection in ASCs is presented in the context of the extant literature. This is accompanied by an overview of the model. Then, each of the four phases of the model is described in more detail. The paper concludes by assessing the potential contribution that the application of the model could make to supplier selection in ASCs. Future research that is required to address its limitations is also identified.

FOUR-PHASE CONCEPTUAL MODEL FOR SUPPLIER SELECTION IN ASCs

The model depicts supplier selection as a four phase process. This is illustrated in Figure 1 as a two-dimensional framework.

[Figure 1 to be inserted here]

The horizontal axis depicts the extent of information available to the purchasing organization, ranging from low to high. The vertical axis depicts the number of combinations of potential suppliers, ranging from many to few. As the selection process advances from phase 1 to 4, the information available becomes more detailed, whilst the number of potential combinations reduces. This step-by-step approach offers an effective means of solving what would otherwise be a highly complex problem. The four phase conceptual model comprises the following phases:

Supplier selection preparation Before any decision about which supplier to select, decision-makers need to have a clear set of criteria against which to assess potential suppliers. Thus, in the first phase of the model, decision-makers prepare for supplier selection by developing a set of customized criteria. This is done via a three stage process that reduces a generic list of criteria, in turn into a prioritised list of industry specific criteria and then to a set of optimal criteria based on the beliefs of the decision-makers. Use of the Dempster-Shafer and optimisation theories enables this to be done under conditions of resource constraint, which is typically the case in any organizational decision-making situation.

Pre-classification This phase enables decision-makers to reduce what might be a very long list of possible suppliers of a particular product to a shortlist of potential suppliers from which a final selection can subsequently be made. It does this by applying the criteria developed in phase 1 using radial basis function artificial neural networks (RBF-ANN) to all possible suppliers against multiple criteria using both quantitative and qualitative measures. This phase also offers an addition refinement by categorising suppliers into different types based on the well-known model from Kraljic (1983). This enables decision-makers to select suppliers from amongst those in the category that is most appropriate to their supply strategy.

Final selection This phase enables decision-makers to choose the most appropriate suppliers from the shortlist provided in phase 2 as well as allocate the order quantities to each that will optimize the performance of the entire supply chain. This is done through the use of an analytic network process-mixed integer multi-objective programming (ANP-MIMOP) model.

Application feedback In the last phase, decision-makers use a combination of qualitative and quantitative methods to assess the application of the previous three phases. Using principles of continuous improvement, the strengths and weaknesses of the selection process are identified in order to improve subsequent applications of the decision making cycle.

More details of each of these phases are provided in the next section of the paper.

Phase 1: Supplier selection preparation

The prudent selection of evaluation criteria is critical to the supplier selection decision-making process. Use of inappropriate criteria may not only waste valuable evaluation resources (e.g. time and money), but will also increase the chances of not selecting the most appropriate supplier. Furthermore, it is also important to limit the number of evaluation criteria to be used. The more criteria that are used, the greater the chance of there is of interdependencies between them, risking decision-making becoming more complex and less effective, as well as more resource-consuming.

The approach taken in the phase follows that of Lin and Chen (2004) in formulating a set of optimal criteria for supplier selection based on an analysis of the distinctive features of the industry from which the supplier as to be selected. However, their approach is likely to be seen as too complex by organizational decision-makers and hence is unlikely to be widely adopted in practice. In order to overcome such criticisms, we propose the following amendments to Lin and Chen's (2004) framework:

(1) Shift the focus of the method to the choice of the most appropriate criteria for supplier selection. This will facilitate a much more in-depth consideration of supplier selection criteria than is to be found in any other existing methods. Lin and Chen's focus was much more on the performance of the supply chain as a whole. They paid very little attention to the selection of individual suppliers.

(2) Conflating Lin and Chen's two main categories of supplier selection criteria into one. This simplifies the supplier selection process and makes the application of the Dempster-Shafer theory much more practicable.

(3) Incorporating sensitivity analysis into the supplier selection process. Sensitivity analysis can provide managers with an improved understanding of how they can make most effective use of the resources at their disposal during the supplier selection process.

(4) Expanding the consideration of resource constraints to include time and human resources as well as money. This more closely mimics the real-life situation faced by organizational decision-makers, who typically find it difficult, if not impossible, to translate resources into monetary values. This refinement could be further expanded to incorporate additional constraints such as information accessibility, government regulations and so on.

As a basis for achieving simplification, a three-stage model is proposed. Its initial stage is that of generating a set of general hierarchy criteria (GHC) for supplier selection which could be applied to any industry. This will be compiled on the basis of a literature survey of potential supplier attributes. The second stage is that of developing a set of industry-oriented hierarchy criteria (IHC), which is relevant only to the industry under consideration. The IHC is extracted from the GHC on the basis of the judgement of organizational decision-makers (managers and/or experts). Since the accuracy of the information about the selected supplier attributes is likely to vary, a basic acceptability index is assigned by the decision-makers to each of the chosen evaluation attributes. Thus, the third stage, is that of formulating a set of optimal hierarchy criteria (OHC), from the IHC by optimizing the total belief acceptability level under limited evaluation resources. Figure 2 shows the proposed model and the relationships between the three sets of criteria.

[Figure 2 inserted here]

These three stages are now described in more detail.

General hierarchy criteria formulation

From a review of the relevant literature including that cited by Lin and Chen (2004) and that subsequently published, it is possible to identify 116 generic supplier evaluation criteria that could be applied in any industry. Cognizant of the need to limit the number of categories, we assign these into seven main categories: Production and logistics management, Partnership management, Financial capability, Technology and knowledge management, Marketing capability, Industrial and organizational competitiveness, Human resource management. A commonly used approach to solving complex multiple-attribute decision-making problems is to adopt a hierarchical structure. These categories are thus used as the second level in the hierarchy that will be used to address this problem of supplier evaluation.

[Take in Table I about here]

Thus the set of general hierarchy criteria (GHC), the constituent elements that comprise the third level of the hierarchy which make up each of these seven criteria and the literature from which they are derive are listed in Tables II – VIII.

[Take in Tables II – VIII about here]

Industry-oriented hierarchy criteria formulation

A set of industry-oriented hierarchy criteria (IHC) is extracted from the GHC by considering that industry’s individual business characteristics. Using a GHC as the basis for IHC has two main advantages, namely adaptability and flexibility. Based on the different characteristics of each individual industry, the GHC can be tailored and adapted to meet its specific needs under evaluation resources constraints. However, there are dependencies between the criteria in the GHC, which is a common phenomenon in multi-attribute decision-making problems. For any of the criteria that they select, decision-makers can form any meaningful combination out of the sub-criteria in the lower layer and generate the subordinate sets of criteria for the IHC.

Also, because the information on evaluation criteria that is available to decision-makers may be incomplete and inaccuracy, there is always some risk of judgement bias. However, this can be accounted for by use of the Dempster-Shafer theory. This is based on developing a belief acceptability index to represent the bias of decision-makers due to information uncertainty.

An illustrative example of the IHC is shown in Figure 3, where $V_{lk} = \cup_k \Gamma_{lik} = \{y_{li} | y_{li} \in \Gamma_{lij}, \forall j\}$ represents the subordinate attributes set in the lower layer of the master evaluation attribute, y_{li}. (N.B. The notations used within the Dempster-Shafer theory (DST), are set out in Table IX.)

[Figure 2 inserted here]
[Take in Table IX about here]

The belief acceptability of any criteria equates to the lower bound of the belief interval (Guan and Bell, 1991). The value of the belief acceptability of a criterion is calculated from the summation of the basic acceptabilities of its all subordinate attributes sets, as follows:

$$\pi_{li} = \sum_{\Gamma_{lij} \subset V_{lk}} m(\Gamma_{lij}) \text{ and } \sum_{j=1}^{V_{lk}} \mathrm{m}(\Gamma_{\mathrm{lij}}) = 1 \quad (1)$$

The procedures to calculate the resultant belief acceptability of the IHC can be summarized as follows:

- Step 1. Let $l = L$, where L is the total number of layers of the IHC. $\forall i$, calculate the belief acceptability π_{Li}, of y_{Li}.
- Step 2. Let $l = L - 1$. $\forall i$, compute π_{li} of y_{li} based on Equation (1).
- Step 3. $\forall i$, repeat step 2 and calculate π_{li} for $y_{(L-3)i}$, $y_{(L-4)i}$, . . ., y_{1i}, and y_{11}, respectively, y_{11} is the resultant favourability attribute of the IHC.

Optimal hierarchy criteria formulation

When tackling a practical ASC supplier selection problem, there are big costs associated with acquiring the performance information of potential suppliers against the various performance criteria. However, before deciding on the most favourable potential supplier, it is the decision maker's responsibility to ensure that the information obtained is as complete and accurate as possible within the timing and budgetary constraints. The objective is to determine the final evaluation criteria (OHC) which possess the maximum total belief acceptability.

This is done by developing a 0-1 nonlinear programming model which is used to generate the OHC of evaluation criteria under limited evaluation resources. The optimal belief acceptability model and constraints for the evaluation criteria are introduced as follows:

Max (the total belief acceptability of OHC)

$$= \max \left(\sum_{l} \sum_{i} \pi_{li} \times U_i \right) \quad (2)$$

Subject to:

$$\sum_{i} c_{ik} \times U_i \le t_k \qquad \forall k \quad (3)$$

$$U_i = 0 \text{ or } 1 \qquad \forall i \quad (4)$$

In the model above, Equation (2) is the objective function of the zero-one nonlinear programming model to optimize the total belief acceptability of the OHC. Inequality (3) constrains the total assigned resources of obtaining information to be equal or less than the available amount of the resources. Lastly, Equation (4) constrains the values of the criteria selection variables to be binary.

Phase 2: Pre-classification

We propose to use a radial basis function-artificial neural network (RBF-ANN) information processing model for this phase of the supplier selection process.

Selecting which suppliers to choose from amongst the very large number of that are potentially available is undoubtedly a daunting task. It therefore makes sense for purchasing organizations to reduce the number of potential combinations to a more manageable level (Swift, 1995; Parker and Hartley, 1997) by applying some kind of screening method. We propose to use Kraljic (1983)'s model to categorize potential suppliers into one of four types according to two variables, namely their impact on the purchasing organization's bottom line and the degree of supply risk involved. Combining these variables yields a two by two matrix, each of whose quadrants characterize four different types of supplier (see Figure 4).

[Figure 4 inserted here]

The strength of Kraljic's model is that its portfolio approach to the categorization of suppliers enables the purchasing organization to adopt strategies appropriate to each type. Using this categorization at the pre-classification stage in the supplier selection process will enable purchasers to identify suppliers which can best meet their needs in each category.

A weakness with Kraljic's model is that it is purely qualitative in nature, relying on the subject judgment of managers to assess a supplier's position on the matrix. It would be more effective if a means could be devised to quantify the criteria used for placement within the matrix. An effective way of doing this would be to use 1 and 0 to represent high and low supply risk and suppliers impact on financial results respectively. Thus, for example, (0,1) would represent leverage suppliers and (1,0) would represent the preference suppliers. The use of Kraljic's matrix alongside RBF-ANN enables the otherwise very daunting task of evaluating all potential suppliers against on all required criteria to become a practical proposition.

Moody and Darken (1989) initially proposed a RBF-ANN, which had only one hidden layer's feed forward network. The RBF-ANN is a particular type of ANN model. RBF-ANNs typically have three layers: an input layer, a hidden layer with a non-linear RBF activation function and a linear output layer. RBF-ANN offers an efficient alternative to the standard multi-hidden-layer ANN. For RBF-ANN, activation of the hidden units is controlled by the distance between the input vector and a prototype vector or centre. This architecture has the advantage that once the centres are determined, network estimation reduces to a linear least squares problem (Blake and Kapetanios, 2000). This kind of ANN can simulate any function within any precision. Use of a RBF-ANN offers the means of developing an information processing model to classify potential suppliers and reduce the solution space of the problem.

Thus, we construct a three-layer feed forward network, comprising an input layer, hidden layer and output layer. The hidden layer applies the radial basis function, which is a Gauss function, as the activation function. The inputs of every neural cell in the hidden layer are the differences between the weight vector W_{ij} of input layer and the input vector x^q multiplied by the threshold value b_j. The values of W_{ij} and b_j are determined by the RBF-ANN's precision and accuracy when the network is being constructed (Moody and Darken, 1989). Thus, the inputs of i^{th} neural cell in the hidden layer are:

$$t_i^q = \sqrt{\sum_j (W_{ij} - x_i^q)^2} \times b_j \qquad \text{for each } i \qquad (5)$$

where, $i = [1, 2, \ldots, I]$ and I equals the numbers of neural cell on the input layer;

$j = [1, 2, \ldots, J]$ and J equals the numbers of neural cell on the hidden layer;

$q = [1, 2, \ldots, Q]$ and Q equals the numbers of input vectors.

The outputs of j^{th} neural cell in hidden layer are:

$$r_j^q = \exp(\sqrt{\sum_j (W_{ij} - x_i^q)^2} \times b_j) \qquad \text{for each } j \qquad (6)$$

The inputs of output layer are weighted sum of the output of the hidden layer. As the activation function is pure linear function, the output is:

$$y_k^q = \sum_j (r_j \times V_{jk}) \qquad \text{for each } k \qquad (7)$$

where, $k = [1, 2, \ldots, K]$ and K equals to the numbers of neural cell on the output layer.

The threshold value b_j can adjust the precision of the function while adjusting its own value though the network training phase**.** However, in practice, a parameter C (the 'expanded constant') is commonly used. Generally, $b_j = 0.8326 / C_j$.

Once the network testing phase has been successfully completed, the RBF-ANN information processing model is ready to use. The training and testing of a RBF-ANN can be achieved efficiently using a simple and robust supervised clustering algorithm (Chen et al, 1993).

The resulting RBF-ANN information processing model proposed is depicted in Figure 5. The neural cells of the input layer equate to the number of sub-criteria in the hierarchy criteria. The number of output neural cells depends on how many types of potential suppliers are required to be classified. In this case, the aim is to classify potential suppliers into one of the 4 types. So there needs to be at least two neural cells in the output layer. [As noted above, we use (0, 0) to represents a routine supplier; (0, 1) for a leverage supplier; (1, 0) for a preference supplier and (1, 1) for a strategic supplier]. A RBF-ANN can fulfil the mapping task from N-dimensions to M-dimensions. So, this model enables the purchasing organization to classify potential suppliers into one of the four categories.

[Figure 5 inserted here]

Given a set of potential suppliers, decision-makers can use the model to assess the potential suppliers against pre-determined criteria. Its use in this pre-classification phase enables suppliers to be divided into one of the four categories (strategic suppliers, preference suppliers, leverage suppliers or routine suppliers) speedily and at low cost.

Phase 3: Final selection

This phase of the model is based on the use of ANP-MIMOP. The main reasons for applying both ANP and MIMOP methodologies are twofold. Firstly, the problem of final selection in ASC is extremely complicated. If we use only one of them (as Feng and Yamashiro (2003), Narasimhan et al. (2006), Gencer and Gurpinar (2007) do) the problem can not be solved efficiently and effectively. Secondly, the two methods are mutually reinforcing, in that the shortcomings of one method are compensated for by the strong points of the other. On the one hand, ANP can consider the complex relationships between factors and clusters, but can not solve the detailed sourcing problem, such as optimization of order quantities allocation. On the other hand, MIMOP can solve the optimization of order quantities allocation problem efficiently and effectively. However, it can not consider the internal and external relationships between the factors/clusters which are very important in ASC supplier selection (Sarkis et al., 2007). Using them in combination increases the chances of solving the problem more effectively and efficiently.

To overcome the inherent complexity of the final selection, we can divide the problem into two sub-problems:

(1) *Obtaining the proprieties of different criteria.* The approach to solving this sub-problem involves applying an ANP methodology to consider the internal and external relationships between factors and clusters of the complex system problem.

(2) *Optimizing the allocation of order quantities to the most suitable potential suppliers.* This uses the MIMOP approach because of its simplicity and flexibility. Bids from potential suppliers can be evaluated with respect to the priorities of criteria obtained from the solution of the first sub-problem.

The general steps of the proposed ANP-MIMOP model for supplier selection are shown in Figure 6.

[Figure 6 inserted here]

One of the key issues in selecting appropriate suppliers for an ASC is that of determining which criteria to use in order to assess their performance (Christopher, 2000; Sarkis et al., 2007). For the purposes of this paper, we use the four major performance measures most typically identified in the agility literature as being the most important, namely cost, quality, time, and flexibility (Dove, 1994; Meade and Sarkis, 1999; Yusuf, et al., 1999; Arteta and Giachetti, 2004). The importance of these criteria can be traced back to the classical works of Wheelwright (1978) and others in the areas of operations and strategy (Ren et al., 2003; Sarkis et al., 2007). Vokurka and Fliedner (1998) argued that although the number of these competitive priorities and performance measures has increased over the years, they can still be grouped under these four main headings.

Based on these four groups of performance criteria, we build our ANP network structure as shown in Figure 7. The relationships between and within the different clusters are on the extant supply chain performance literature, notably Katayama and Bennett (19990, Naylor et al. (1999), Subbu et al. (1999), Christopher (2000), Power et al. (2001), Prater et al.(2001) and Stratton and Warburton (2003).

[Figure 7 inserted here]

Figure 7 shows the four main criteria (with FC representing the flexibility criterion, QC the quality criterion, etc.). As noted, each of the four main criteria is comprised of various subcriteria, with, for example, FC, relationships establishment being used to evaluate the complexity and flexibility of the formation an ASC.

According to the relationship between and within the clusters, we need to pairwise compare (PWC) the factors between the factors/clusters by using inputs from organizational decision makers. Saaty (1980) suggests that the values assigned to the comparisons of the factors be made in the range 1/9 to 9. A 9 indicates that one factor is extremely more important than the other; a 1/9 indicates that one factor is extremely less important than the other, and a 1 indicates equal importance. In this step, the consistency of each comparison is also checked.

Next, we can build an unweighted supermatrix, which could yield the weighted criteria we require, according to the ANP network (shown in Figure 7) and the PWCs. Each column of the supermatrix is either a normalized eigenvector or its entire block entries are zero. The unweighted supermatrix in this paper covers all the components in the ANP network. The generalized form of the unweighted supermatrix is shown in Figure 8.

[Figure 8 inserted here]

In Figure 8, $W_{CC,K}^{TC}$ represents that cluster CC depends on cluster TC, etc. Also the clusters, which have no interaction, are shown in the supermatrix with zero. Since there is usually interdependence among clusters in a network, the columns of an unweighted supermatrix usually sum to more than one. The supermatrix must be transformed first, to make each column of the matrix sum to unity by determining the relative importance of the clusters in the unweighted supermatrix with the column cluster as the controlling component (Meade and Sarkis, 1999). With pairwise comparison matrix of the row components with respect to the column component, an eigenvector can be obtained. For each column cluster, the first entry of the respective eigenvector is multiplied by all the elements in the first cluster of that column, the second by all the elements in the second cluster of that column and so on. In this way, the clusters in each column of the supermatrix are weighted, and the result is the weighted supermatrix.

Finally, to achieve a convergence on the importance weights, the weighted supermatrix is raised to the power of $2n+1$, where n is an arbitrarily large number, and this new matrix is the limiting supermatrix (Saaty, 1996). By normalizing each block of this limiting supermatrix, the final priorities of all the elements in the matrix can be obtained.

The next stage in the process is that of determining how to form the most reasonable structure of ASC and assign the most suitable order quantities to the most appropriate suppliers. This requires the application of the MIMOP method.

For simplicity, this can be illustrated by its application to a basic supply chain that comprises constituents of suppliers, producers, distribution centres and customer zones. This is depicted in Figure 9. Relevant notations are shown in Table X.

[Figure 9 inserted here.]

[Take in Table X about here.]

This study assumes that the objective of the model is to seek pareto-optimal solutions for the whole supply chain for the following factors:

(1) Material cost. The whole ASC seeks to minimize the cost of raw materials which are supplied by different suppliers. Thus, the objective function can be stated as:

$$\textbf{Min.} \quad obj_1 = w_1 \times \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{J}(MC_{rij} \times SPQ_{rij}) \qquad (8)$$

(2) Production cost. At the same time, the whole ASC seeks to minimize the production cost when product *s* is produced by producer *j*.

$$\textbf{Min.} \quad obj_2 = w_2 \times \sum_{s=1}^{S} \sum_{j=1}^{J} [(\sum_{k=1}^{K} PDQ_{sjk}) \times PC_{sj}] \tag{9}$$

(3) Transportation complexity. Maximising the efficiency of the whole supply chain requires that the complexity of transportation be minimised. This model uses total transportation cost (including the time cost) to evaluate the complexity of product transportation. Equation (10) expresses this objective as the minimization of transportation cost of product *s* from producer *j* to DC *k*.

$$\textbf{Min.} \quad obj_3 = w_3 \times \sum_{s=1}^{S} \sum_{j=1}^{J} \sum_{k=1}^{K} (TC_{sjk} \times PDQ_{sjk}) \tag{10}$$

(4) Distribution efficiency. For the same reason to maximize the efficiency of the distribution of products, this model requires the minimization of the total distribution cost (including the time cost). This can be defined as minimizing the distribution cost of product *s* from DC *k* to customer zone *m*.

$$\textbf{Min.} \quad obj_4 = w_4 \times \sum_{s=1}^{S} \sum_{k=1}^{K} \sum_{m=1}^{M} (DC_{skm} \times DCQ_{skm}) \tag{11}$$

(5) Establishment flexibility. This study uses the establishment cost concept to express and calculate the complexity and flexibility of the formation an ASC.

$$\textbf{Min.} \, obj_5 = w_5 \times [\sum_{i=1}^{I} \sum_{j=1}^{J} (ECA_{ij} \times x_{ij}) + \sum_{j=1}^{J} \sum_{k=1}^{K} (ECB_{jk} \times y_{jk}) + \sum_{k=1}^{K} \sum_{m=1}^{M} (ECC_{km} \times z_{km})] \tag{12}$$

(6) Quality level. This expression minimizes the defective rate for every kind of product and rewards the producers with higher quality performance levels.

$$\textbf{Min.} \quad obj_6 = w_6 \times \sum_{s=1}^{S} \sum_{j=1}^{J} \left(\frac{\sum_{k=1}^{K} PDQ_{sjk}}{\sum_{j=1}^{J} \sum_{k=1}^{K} PDQ_{sjk}} \times DR_{sj} \right) \tag{13}$$

(7) Service level. For the any given level of customer demand, this expression maximizes the total service level of the customer zone and rewards the customer zone with higher satisfaction levels.

$$\textbf{Max.} \quad obj_7 = w_7 \times \sum_{s=1}^{S} \sum_{m=1}^{M} SL_{sm} \tag{14}$$

There are a number of constraints that need to be taken into account:

(1) Material balance. There may be material constraints arising from the competing demands of different product structures, as indicated in a Bill of Material (BOM). Thus, if one unit of product *s* needs MR_{rs} units of raw material *r*, these constraints can be expressed as:

$$MR_{rs} \times \sum_{k=1}^{K} PDQ_{sjk} = \sum_{i=1}^{I} SPQ_{rij} \qquad \forall \; s, r, j \tag{15}$$

(2) Supplier's capacity limit. As supplier i can provide up to SCL_{ri} units of raw material *r* and its order quantities SPQ_{rij} should be equal or less than its capacity, these constraints are:

$$\sum_{j=1}^{J} SPQ_{rij} \le SCL_{ri} \qquad \forall \; r, i \qquad (16)$$

(3) Production capacity limit. As producer j can produce up to PCL_{ij} units of product s and its order quantities PDQ_{sjk} should be equal or less than its capacity, these constraints are:

$$\sum_{k=1}^{K} PDQ_{sjk} \le PCL_{sj} \qquad \forall \; s, j \qquad (17)$$

(4) Distribution centre throughput limit. As DC k can distribute up to DCL_{sk} units of product s and its distribution quantity DCQ_{skm} should be equal or less than its capacity limit, these constraints are:

$$\sum_{m=1}^{M} DCQ_{skm} \le DCL_{sk} \qquad \forall \; s, k \qquad (18)$$

(5) Total supply and total demand limit. As sum of the assigned order quantities from a DC should meet the customer zone's demand, it can be stated as:

$$\sum_{k=1}^{K}\sum_{m=1}^{M} DCQ_{skm} \le \sum_{m=1}^{M} TD_{sm} \qquad \forall \; s \qquad (19)$$

(6) Defective rate constraints. Since DR is the ASC's maximum acceptable defective rate of all products and DR_{sj} is the defective rate of products s produced in producer j, the quality constraints can be shown as:

$$\sum_{j=1}^{J} \left(\frac{\sum_{k=1}^{K} PDQ_{sjk}}{\sum_{j=1}^{J}\sum_{k=1}^{K} PDQ_{sjk}} \times DR_{sj} \right) \le DR \qquad \forall \; s \qquad (20)$$

(7) Distribution centres constraints. Product input quantity should be equal to product output quantity in a single period. It can be stated as:

$$\sum_{j=1}^{J} PDQ_{sjk} = \sum_{m=1}^{M} DCQ_{skm} \qquad \forall \; s, k \qquad (21)$$

(8) Service level definition.

$$SL_{sm} = \frac{\sum_{k=1}^{K} DCQ_{skm}}{TD_{sm}} \qquad \forall \; s, m \qquad (22)$$

(9) Variable constraints.

$$x_{ij} = 0 \text{ or } 1 \qquad \forall \; i, j \qquad (23)$$
$$y_{jk} = 0 \text{ or } 1 \qquad \forall \; j, k \qquad (24)$$
$$z_{km} = 0 \text{ or } 1 \qquad \forall \; k, m \qquad (25)$$
$$SPQ_{rij} \ge 0 \qquad \forall \; r, i, j \qquad (26)$$
$$PDQ_{sjk} \ge 0 \qquad \forall \; s, j, k \qquad (27)$$
$$DCQ_{skm} \ge 0 \qquad \forall \; s, k, m \qquad (28)$$

The model can be easily amended, incorporating more, less or different criteria to suit different decision contexts.

Phase 4: Application feedback

The fourth and final phase of the model is that of application feedback. This attempts to obtain feedback on the implementation of the previous three phases in order to obtain useful information on how to improve subsequent applications of the model. This phase integrates aspects of quality management into supplier selection process. In particular it applies an element of continuous improvement, which as Power et al. (2001) note can be very important in ASCs supplier selection.

A conceptual model for application feedback and continuous improvement in supplier selection is presented in Figure 10. The roles of the quality management system principles in the model are illustrated below.

[Figure 10 inserted here]

The model is based on Deming's (2000) famous Plan Do Check Act (PDCA) cycle model for continuous quality improvement. It views an ASC as a system to communicate the customer's demands throughout the entire chain. The incorporation of this phase into the supplier selection process requires that a philosophy of customer focus and satisfaction becomes integral to the formulation and operation of an ASC. This then gives direction and motivation to the supplier selection process, and acts as the primary input of the whole supplier selection process.

- The *plan* stage can be seen as the formulation of the 4PCM, (shown as Figure 1). This uses a process approach through the use of the DST, RBF-ANN and ANP-MIMOP sub-models and the use of multiple objectives in supplier selection organized in a semi-structured manner.

- The *do* stage is the application of the various sub-models from constructing the optimal hierarchy criteria, building the RBF-ANN network and ANP structure to allocating the right order quantities to the right suppliers. The involvement of people is the key concept underpinning the application of the various sub-models.

- The *check* stage involves validating the structure of the supply chain, the selection of the suppliers and allocation of order quantities by assessing the performance of the entire supply chain. Use of a fact-based approach to decision-making, such as this, will make the choice of supplier more stable.

- The *act* stage involves taking action to address any problems identified in the check stage. These might arise from monitoring the supply chain performance and from reviewing the effectiveness of the process. These improvement processes can be started simultaneously. Once the inefficient or ineffective points are found in the supplier selection sub-models and the selection processes, the ASC needs to adjust the sub-models and the selection processes in the light of the feedback, or even restructure the sub-models to fulfil the changing multiple objectives. A systematic approach is adopted here, based on the documentation of any adjustments and re-structuring undertaken. This stage closes the continuous improvement loop and thus provides an organic mechanism to respond to any changes whether arising from internal requirements or external environment influences (Chan and Chan, 2004). Mutually beneficial relationship will need to be constructed between the different suppliers, if excellent products/services with high quality, low cost and any other objectives are to be achieved, which are the basis of fulfilling the changing needs of customers.

The check stage of the PDCA cycle in this case relies on assessing the potential merits and drawbacks of using the various supplier selection sub-models and approaches in practice. Its aim is to evaluate and investigate the decision-makers' use of the decision tools and provide feedback to inform the subsequent improvement of the earlier decision-making steps.

The proposed approach is built on existing work in the field. Bevilacqua et al. (2006) used seven of the 13 criteria proposed by De Boer and van der Wegen (2003) in their assessment of decision models. However, their focus is not on the supplier model evaluation, but on the supplier selection model construction. We propose to extend the criteria proposed in the above literature to make them more stable, reliable and informational. These are listed in Table XI.

[Take in Table XI about here]

The proposed evaluation method is based on a comparison of a decision situation where the proposed decision-support sub-models are used with a situation where this is not the case. A case study methodology (Yin, 2002) is used to obtain a thorough picture of the actual decision-making processes that take place in a specific situation. Then, an experiment is undertaken in which the decision-makers are asked to re-enact the phases of the decision-making process once more using the proposed decision models. This approach is based on the use of a quasi-experimental methodology (Cook and Campbell, 1979) using the principles of action research (Lewin, 1946).

Thus, the evaluation process consists of three stages:

(1) *Pre-test* - This consists of carefully documenting an actual supplier selection process as it unfolds in an organization. This will provide a reference context with regard to the criteria from Table XI. Data collection is be via focused interviews with the decision-makers involved as well as analysis of relevant documents (e.g. quotations or supplier visit reports).

(2) *Test* - Based upon the detailed information obtained from the pre-test case study, proposed decision-support sub-models are applied to all phases of the supplier selection process. Interventions during the execution of the process are kept to the minimum necessary to ensure the proper execution of the decision-support sub-models and whole selection process.

(3) *Post-test* - After the test, an evaluation of the proposed decision-support sub-models takes place. This is done through semi-structured interviews with the decision-makers, who have been involved in both the experiment and the actual supplier selection processes. These interviews will enable the proposed decision-support sub-models to be evaluated with respect to the criteria shown in Table XI

Use of a pre-test/post-test design, provides a static pictures of the organization before and after the intervention, which can then be used for comparison purposes in order to provide feedback on the previous phases of the supplier selection processes.

CONCLUSION

Efficient ASCs are considered to be the solution to meet the frequently changing customer demands for high quality, short lead times, low costs and high customer service levels. It is generally accepted that the successful performance of an ASC depends heavily on the supply network construction and the choice of the right suppliers.

Furthermore, the process of selecting suppliers has become an increasing complex decision.

The four phase conceptual model presented in this paper, offers a comprehensive and detailed method for tackling the supplier selection problem in ASCs. The approach contained in the model is both rigorous and practical. It improves the supplier selection process in ASCs in three main ways. Firstly, unlike much of the existing literature, it considers the supplier selection process holistically as a complete process. This enables the system as a whole to be optimized, by considering the sequence and connections between different phases. Secondly, it enables the most appropriate methods to be chosen for each of the phases, thereby improving the effectiveness of the process as a whole. In particular, the model enables decision-makers to make use of recent advances in computing that are incorporated within its various techniques. Individually and collectively these offer the prospect of more informed and considered decision-making. Use of the 4PCM provides decision-makers with the capability of making efficient and effective use of the vastly increased amount of data that is available on potential suppliers in today's information driven society. Finally, the use of Kraljic's classification matrix increases the visibility of the assessment of each potential supplier's strength and weakness, enabling decision-makers to make more rational judgments.

There appears to be two main disadvantages to the model. Firstly, determining which factors to take into account is difficult in practice. These must be matched to the objectives of the ASC, which in fast-changing market conditions can be difficult. However, use of the model forces decision-makers to address this issue explicitly, which should improve the decision-making process by ensuring that supplier selection is aligned to strategic objectives. Secondly, the process may appear too complex to some decision-makers when speed is of the essence. Whilst this is likely to be a very real concern initially, it is anticipated that the decision-making process can be conducted much more speedily in subsequent applications of the model.

The next stage of the research will focus on the development and application of the model. This will involve detailed work on each phase to develop the techniques introduced in this paper in sufficient detail to enable them to be applied in practice. Initially this will involve their application under conditions which simulate real world contexts. However, once the efficacy of each phase can be established, it is hoped to apply the model in its entirety, using all four phases in live organizational situations. This would enable the applicability of the model to be confirmed. Any shortcomings that were identified at this stage could then be addressed to further improve and refine the model.

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TABLES

Table I General hierarchy criteria (GHC) for the ASCs supplier selection

Hierarchy level	Selected criteria
1st level	Evaluation for potential suppliers in ASC
2nd level	Production and logistics management Partnership management Financial capability Technology and knowledge management Marketing capability Industrial and organizational competitiveness Human resource management
3rd level	Shown in Tables II-VIII.

Table II Production and logistics management sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,1}$	Production volume flexibility (Sarkar & Mohapatra, 2006)
$y_{3,2}$	Variation in types of products or services (Choy et al., 2003)
$y_{3,3}$	Post-sales service and support (Choi & Hartley, 1996)
$y_{3,4}$	Order lead time (Chung et al., 2005)
$y_{3,5}$	Responsiveness to customer needs (Choy et al., 2003)
$y_{3,6}$	Condition of physical facilities (Chung et al., 2005)
$y_{3,7}$	Design capability (Sarkar & Mohapatra, 2006)
$y_{3,8}$	Cost-reduction capability (Yigin et al., 2007)
$y_{3,9}$	Quality philosophy (Sarkar & Mohapatra, 2006)
$y_{3,10}$	Delivery capacity and reliability (Yigin et al., 2007)
$y_{3,11}$	Distribution network performance and quality (Lin & Chen, 2004)
$y_{3,12}$	Quality assurance system (Yigin et al., 2007)
$y_{3,13}$	Manufacturing network performance (Choi & Hartley, 1996)
$y_{3,14}$	Order fulfilment rate (Narasimhan et al., 2006)
$y_{3,15}$	Average defect rate (Hajidimitriou & Georgiou, 2002)
$y_{3,16}$	Price/cost ratio (Talluri et al. 1999)
$y_{3,17}$	Geographical location (Yan et al., 2003)
$y_{3,18}$	Production capabilities (Talluri, 2002)
$y_{3,19}$	Sophistication of product lines (Choy et al., 2003)
$y_{3,20}$	Capabilities to provide quality product/service (Lin et al., 2006)
$y_{3,21}$	Quality stability (Mikhailov, 2002)
$y_{3,22}$	Volatility of product mix (Talluri, 2002)
$y_{3,23}$	Transportation cost (Narasimhan et al., 2006)
$y_{3,24}$	Service level (Choy et al., 2002)
$y_{3,25}$	Consistent conformance to specifications (Choi & Hartley, 1996)
$y_{3,26}$	Warranty period (Xia and Wu, 2007)

Table III Partnership management sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,27}$	Government relationships (Harvey & Lusch, 1995)
$y_{3,28}$	Information available on supplier (Gencer and Gurpinar, 2007)
$y_{3,29}$	Risk of failure of cooperation (Ip et al., 2003)
$y_{3,30}$	Easy communication (Ngai et al., 2004)
$y_{3,31}$	Willing to invest in sales training (Cavusgil et al., 1995)
$y_{3,32}$	Compatible management styles (Hajidimitriou & Georgiou, 2002)
$y_{3,33}$	Industrial experience (Luo, 1998)
$y_{3,34}$	Cost to integration (Ip et al., 2003)
$y_{3,35}$	Alliance experience (Harvey & Lusch, 1995)
$y_{3,36}$	Willingness to resolve conflict (Choi & Hartley, 1996)
$y_{3,37}$	Financial institution relationship (Harvey & Lusch, 1995)
$y_{3,38}$	Closeness of past relationship (Choi & Hartley, 1996)
$y_{3,39}$	Data information (Ngai et al., 2004)
$y_{3,40}$	Relationship building flexibility (Lin & Chen, 2004)
$y_{3,41}$	Power relative to potential partner (Harvey & Lusch, 1995)
$y_{3,42}$	Company's reputation to integrity (Sarkar & Mohapatra, 2006)
$y_{3,43}$	The stability of the joint venture (Lorange et al., 1992)
$y_{3,44}$	Time needed to integration (Ip et al., 2003)
$y_{3,45}$	Track record with past suppliers (Cavusgil et al., 1995)
$y_{3,46}$	Compatible organization cultures (Hajidimitriou & Georgiou, 2002)
$y_{3,47}$	Foreign experience (Luo, 1998)
$y_{3,48}$	Willingness to reveal financial records (Choi & Hartley, 1996)

Table IV Financial capability sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,49}$	Net Operating Margin (Mikhailov, 2002)
$y_{3,50}$	Asset/Liability ratio (Luo, 1998)
$y_{3,51}$	Gross Profit Margin (Gencer and Gurpinar, 2007)
$y_{3,52}$	The growth rate of business income (Mikhailov, 2002)
$y_{3,53}$	Stockholders' equity ratio
$y_{3,54}$	Cash Flow per Share
$y_{3,55}$	Earnings per share of stock
$y_{3,56}$	Debt/equity ratio (Harvey & Lusch, 1995)
$y_{3,57}$	Inventory turnover
$y_{3,58}$	Liquidity ratio
$y_{3,59}$	Total Revenue (Chung et al., 2005)
$y_{3,60}$	Assets rates of increment (Dacin et al., 1997)
$y_{3,61}$	Net profits growth rates (Lin & Chen, 2004)
$y_{3,62}$	Accounts receivable turnover

Table V Technology and knowledge management sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,63}$	Technical capability (Sarkar & Mohapatra, 2006)
$y_{3,64}$	Cost of alternatives (Narasimhan et al., 2006)
$y_{3,65}$	Technical advice (Dulmin & Mininno, 2003)
$y_{3,66}$	Knowledge of local business practices (Hajidimitriou & Georgiou, 2002)
$y_{3,67}$	Information systems and communication (Yigin et al., 2007)
$y_{3,68}$	Partner's ability to acquire your firm' special skills (Xia and Wu, 2007)
$y_{3,69}$	Obtain partner's local knowledge (Dulmin & Mininno, 2003)
$y_{3,70}$	Patent security (Cavusgil et al., 1995)
$y_{3,71}$	Willingness to share expertise (Ngai et al., 2004)
$y_{3,72}$	Technology innovation (Choy et al., 2003)
$y_{3,73}$	Special skills that you can learn from partners (Dulmin & Mininno, 2003)
$y_{3,74}$	Product Familiarity (Dulmin & Mininno, 2003)
$y_{3,75}$	Equipment status of the partners (Gencer and Gurpinar, 2007)
$y_{3,76}$	Repair turnaround time (Xia and Wu, 2007)

Table VI Marketing capability sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,77}$	Product/service brand value (Luo, 1998)
$y_{3,78}$	Brand loyalty (Harvey & Lusch, 1995)
$y_{3,79}$	Sales force (Cavusgil et al., 1995)
$y_{3,80}$	Local political & cultural environments (Lorange et al., 1992)
$y_{3,81}$	Customer demanded changes
$y_{3,82}$	Rapid market entry (Hajidimitriou & Georgiou, 2002)
$y_{3,83}$	General reputation (Choy et al., 2002)
$y_{3,84}$	Better export opportunities (Hajidimitriou & Georgiou, 2002)
$y_{3,85}$	Experience with target customers (Cavusgil et al., 1995)
$y_{3,86}$	Market position (Luo, 1998)
$y_{3,87}$	Market share (Cavusgil et al., 1995)
$y_{3,88}$	Variation in price (Lin & Chen, 2004)
$y_{3,89}$	Price level (Mikhailov, 2002)
$y_{3,90}$	Culture of customer service (Choy et al., 2002)
$y_{3,91}$	Marketing competence (Luo, 1998)
$y_{3,92}$	Supplier representative's competence (Choi & Hartley, 1996)
$y_{3,93}$	Variation in demand quantity (Talluri, 1999)
$y_{3,94}$	Customer loyalty (Luo, 1998)
$y_{3,95}$	Marketing expertise/knowledge (Harvey & Lusch, 1995)

Table VII Industrial and organizational competitiveness sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,96}$	Strategic position in the marketplace (Harvey & Lusch, 1995)
$y_{3,97}$	Bargaining power of suppliers (Harvey & Lusch, 1995)
$y_{3,98}$	Industry attractiveness (Dacin et al. , 1997)
$y_{3,99}$	Strategic orientation (Luo, 1998)
$y_{3,100}$	Influence on industry (Harvey & Lusch, 1995)
$y_{3,101}$	Rivalry among existing firms (Harvey & Lusch, 1995)
$y_{3,102}$	Complementarity of product lines (Cavusgil et al., 1995)
$y_{3,103}$	Corporate market position (Harvey & Lusch, 1995)
$y_{3,104}$	Functional competencies (Sarkar & Mohapatra, 2006)
$y_{3,105}$	Bargaining power of buyers (Harvey & Lusch, 1995)
$y_{3,106}$	Relative power of organization (Harvey & Lusch, 1995)
$y_{3,107}$	Unique competencies (Dacin et al., 1997)
$y_{3,108}$	Threat of substitute products (Harvey & Lusch, 1995)

Table VIII Human resource management sub-criteria in 3rd level of GHC

Index	Criteria details
$y_{3,109}$	Entrepreneurial creativity (Harvey & Lusch, 1995)
$y_{3,110}$	Quality of local personnel (Sarkar & Mohapatra, 2006)
$y_{3,111}$	Human resource management skill (Yigin et al., 2007)
$y_{3,112}$	Learning ability (Luo, 1998)
$y_{3,113}$	Organizational leadership (Luo, 1998)
$y_{3,114}$	Product and market expertise (Cavusgil et al., 1995)
$y_{3,115}$	Corporate culture (Talluri et al., 1999)
$y_{3,116}$	Quality of management team (Cavusgil et al., 1995)

Table IX Notations used in the Dempster-Shafer theory

l	layer index of configuration hierarchy, l = 1,2, . . . , L
y_{li}	the evaluation attribute i in layer l
y_{Li}	the evaluation attribute i which always located in the bottom layer of the attribute configuration hierarchy
y_{11}	the final aggregate evaluations attribute
V_{lk}	the k^{th} set of selected attributes s in layer l
Γ	a general notation to represent the subordinate attributes set
Γ_{11j}	the j^{th} subordinate attributes set of the final aggregate evaluation attribute
Γ_{lij}	the j^{th} subordinate attributes set of its master attribute y_{li}
$m(\cdot)$	the basic probability assignment function of a given proposition
$m(\Gamma_{lij})$	the belief acceptability for Γ_{lij} of the master attribute y_{li}
π	a general notation to represent the acceptability of an evaluation attribute
π_{li}	the belief acceptability of the subordinate evaluation attribute y_{li}
U_i	the binary attribute selection variable that if the evaluation attributes is selected, then U_i = 1; otherwise U_i = 0
t_s	total available amount of evaluation resource s, $s = 1,2, \ldots , S$
c_{is}	the unit consumption rate of evaluation resource s to acquire information of evaluation criterion y_{Li}

Table X Notations used in the MIMOP

i	is the index for a supplier, i = 1,2, … , I
j	is the index for a producer, j = 1,2, … , J
k	is the index for a distribution centre (DC), k = 1,2, … , K
m	is the index for a customer zone, m = 1,2, … , M
r	is the index for a raw material, r = 1,2, … , R
s	is the index for a product, s = 1,2, … , S
x_{ij}	a 0-1 variable indicating whether material r is supplied by supplier i to producer j ($x_{ij} = 1$) or not ($x_{ij} = 0$)
y_{jk}	a 0-1 variable indicating whether product s is shipped by producer j to DC k ($y_{jk} = 1$) or not ($y_{jk} = 0$)
z_{km}	a 0-1 variable indicating whether product s is distributed by DC k to customer zone m ($z_{km} = 1$) or not ($z_{km} = 0$)
SPQ_{rij}	total units of raw material r purchased from supplier i to producer j
PDQ_{sjk}	total units of product s shipped from producer j to DC k
DCQ_{skm}	total units of product s shipped from DC k to customer zone m
SL_{sm}	service satisfaction level in customer zone m for product s
MC_{rij}	unit cost of raw material r ordered from supplier i to producer j
PC_{sj}	unit production cost of product s in producer j
TC_{sjk}	unit transportation cost of product s from producer j to DC k
DC_{skm}	unit distribution cost of product s from DC k to customer zone m
ECA_{ij}	establishment cost for supplier i with producer j
ECB_{jk}	establishment cost for producer j with DC k
ECC_{km}	establishment cost for DC k with customer zone m
TD_{sm}	total customer demand for product s in customer zone m
DR	defective rate threshold level of the whole supply chain
DR_{sj}	defective rate of product s from producer j
MR_{rs}	material requirement rate for one unit product s needs the units of material r
SCL_{ri}	supplier i^{th} capacity limit to supply material r
PCL_{sj}	production capacity limit of producer j for product s
DCL_{sk}	distribution limit of DC k to distribute product s
w_p	the different weights of p^{th} main criterion

Table XI Criteria for evaluation of the models for supplier selection

Dimensions	Criteria
Complexity-fit	C1: Do the models aggregate information in a proper way?
	C2: Do the models sufficiently utilise available information?
	C3: Do the models easy to use?
	C4: Do the models ask for too much time?
	C5: Is it (to a satisfactory extent) possible to incorporate opinions and beliefs?
	C6: Is it (to a satisfactory extent) possible to achieve a fair participation of individual members in case of a group decision?
	C7: Are the models sufficiently flexible for changes in the decision situation?
Cost/benefit	C8: Is the outcome of the decision models useful?
	C9: Is the outcome of the decision models accuracy?
	C10: Is the outcome of the decision models acceptable?
	C11: Are the required investments justifiable?
	C12: Are the models sufficiently user-friendly?
	C13: Is the way the decision models work sufficiently clear?
	C14: Do the decision models increase the insight in the decision situation?
	C15: Do the decision models contribute to the communication about and the justification of the decision?
	C16: Do the decision models contribute to your decision making skills?

FIGURES

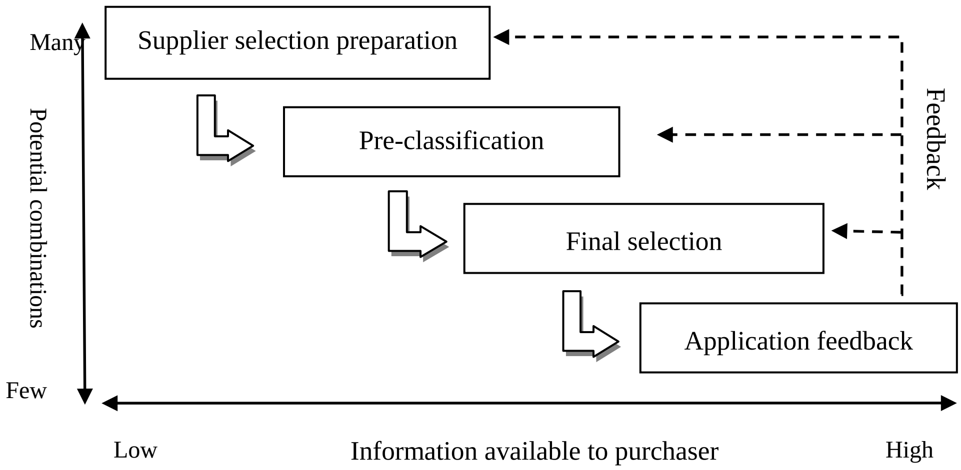

Figure 1 Four phase conceptual model for supplier selection in ASC

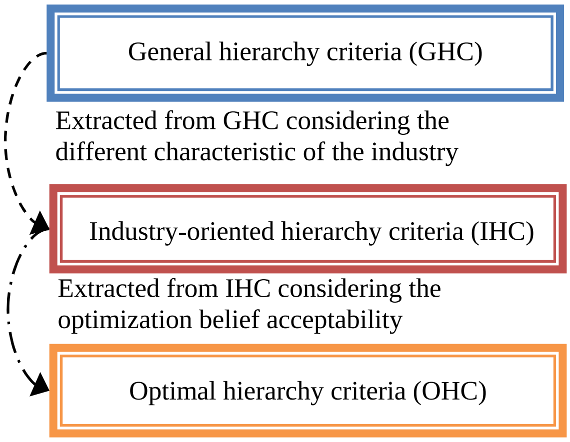

Figure 2 Three-stage model for supplier selection criteria formulation in ASCs

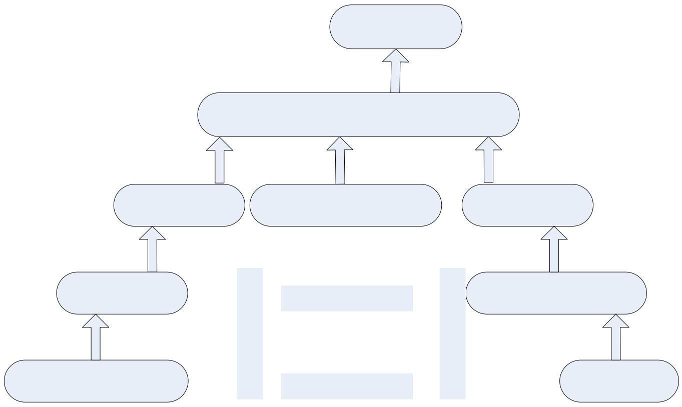

Figure 3 Industry-oriented hierarchy criteria formulation example

$y_{(L-}$

y_{L1} y_{L2}

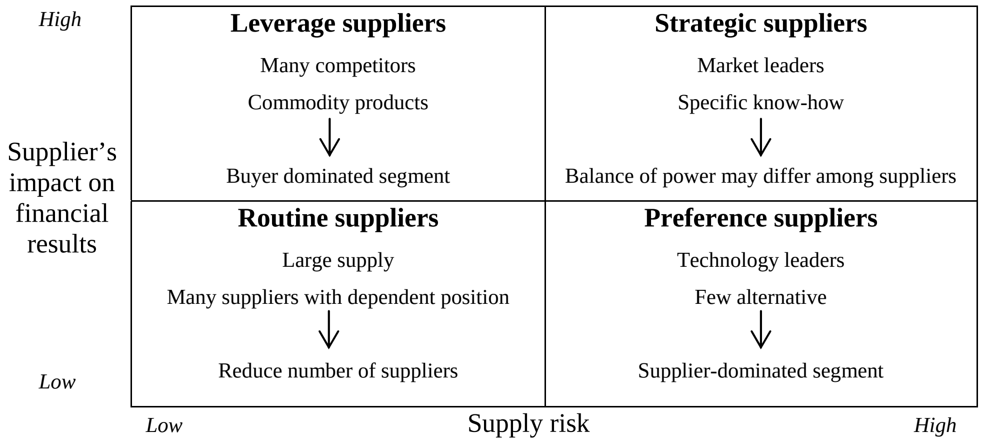

Figure 4 Classification matrix of suppliers (Kraljic, 1983)

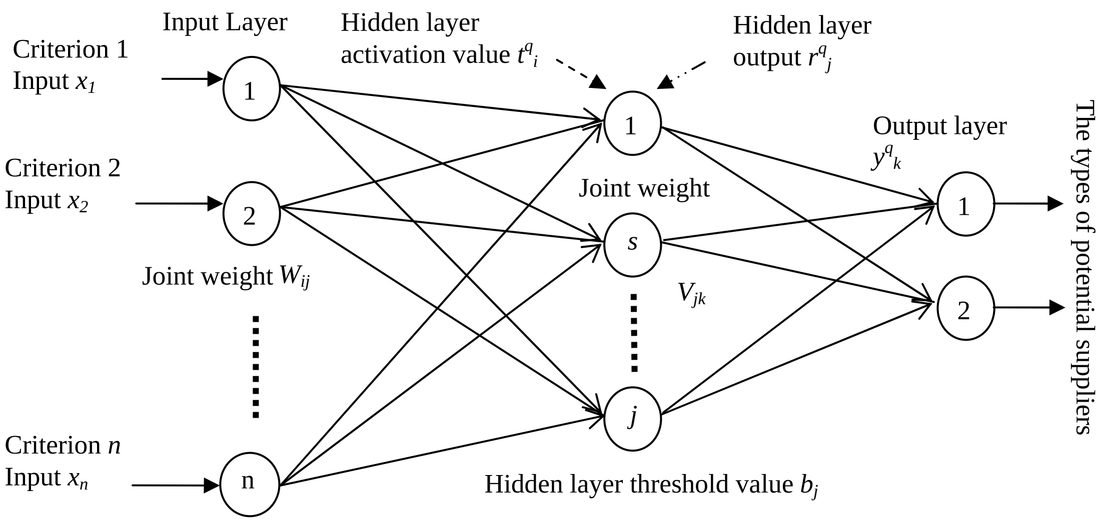

Figure 5 RBF-ANN supplier selection information processing model

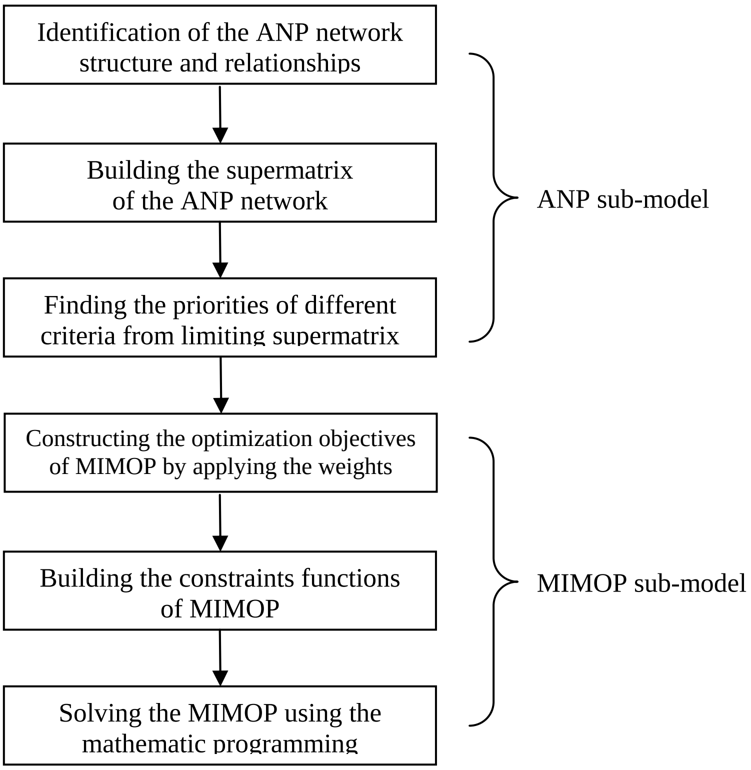

Figure 6 The general steps of ANP-MIMOP model for final phase supplier selection in ASCs

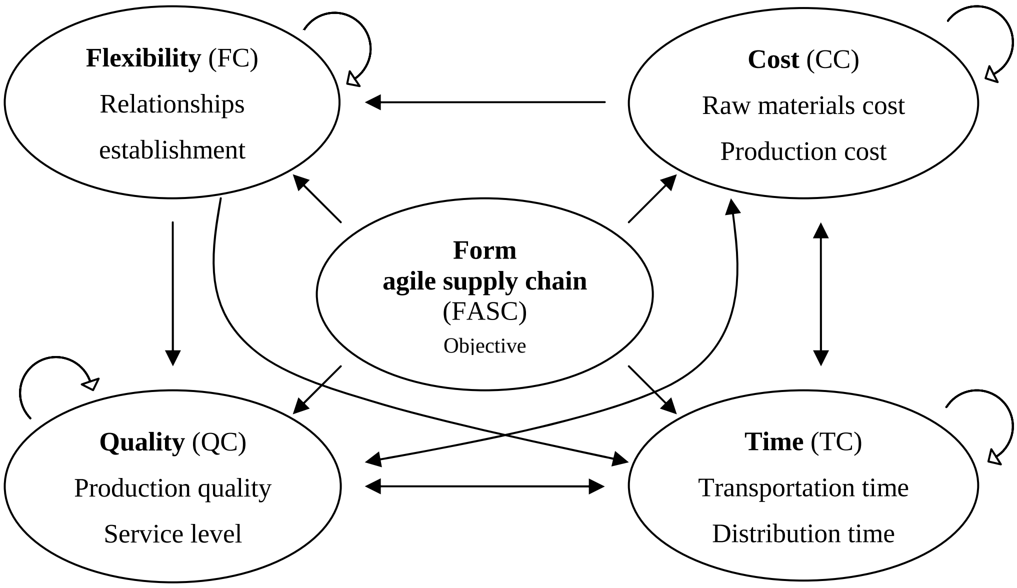

Figure 7 The ANP network structure and relationships between clusters for supplier selection

	FASC	CC	TC	QC	FC
FASC	0	0	0	0	0
CC	$W_{CC,K}^{FASC}$	$W_{CC,K}^{CC}$	$W_{CC,K}^{TC}$	$W_{CC,K}^{QC}$	0
TC	$W_{TC,K}^{FASC}$	$W_{TC,K}^{CC}$	$W_{TC,K}^{TC}$	$W_{TC,K}^{QC}$	$W_{TC,K}^{FC}$
QC	$W_{QC,K}^{FASC}$	$W_{QC,K}^{CC}$	$W_{QC,K}^{TC}$	$W_{QC,K}^{QC}$	$W_{QC,K}^{FC}$
FC	$W_{FC,K}^{FASC}$	$W_{FC,K}^{CC}$	0	0	$W_{FC,K}^{FC}$

Figure 8 The generalized form of the unweighted supermatrix for supplier selection

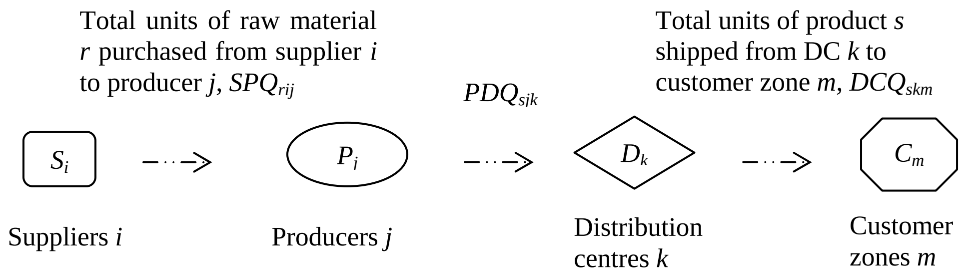

Figure 9 The positions of different supply chain partners and their notations

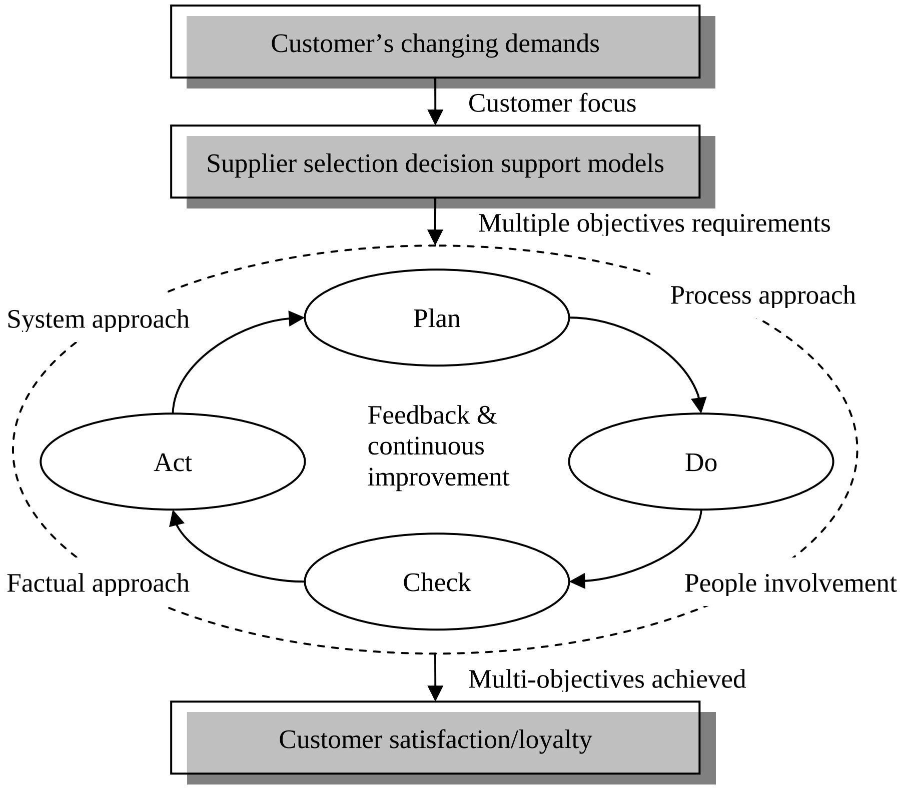

Figure 10 Application feedback and continuous improvement conceptual mode in ASC supplier selection