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Supplier selection and order allocation with process performance index in supply chain management

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Abstract: The need to gain a global competitive advantage on the supply side has forced businesses to search for effective supply network strategies. The effective selection of suppliers is the key ingredient for the success of supply networks. A variety of analytical methods ranging from simple weighted techniques to complex mathematical programming approaches have been proposed for supplier selection. However, these models are generally aimed at supporting a decision maker (DM) in the final selection phase and they have failed to consider a holistic view of the supplier selection process. Supplier evaluation and selection problems are inherently multi-criteria decision problems. Supply networks are now not only configured by suppliers, but also consist of manufacturers, retailers and customers. Therefore, a holistic and comprehensive approach for evaluating these elements in supply networks is required. We propose a multi-objective mathematical programming approach to select the most appropriate supply network elements. The process performance index (PPI) is used as an assessment tool for the supply network elements and the analytic hierarchy process (AHP) is used to integrate the objectives of the proposed mathematical programme to a single one. The efficacy and applicability of the proposed methodology is demonstrated with a numerical example.

Keywords: supply network; process performance index; PPI; mathematical programming; decision making.

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1 Introduction

Supplier selection has a critical effect on the competitiveness of the entire supply chain network. Lewis (1943, p.249) suggested "It is probable that of all the responsibilities which may be said to belong to the purchasing officers, there is none more important than the selection of a proper source. Indeed, it is in some respects the most important single factor in purchasing". England and Leenders (1975) made the same suggestion by stating "supplier selection is purchaser's most important responsibility".

There is a plethora of research on the supplier selection process. Weber et al. (1991) grouped the quantitative methods for supplier selection into three categories: linear weighting models, mathematical programming models and statistical models. In linear weighting models, a weight is assigned to each criterion and a total score for each supplier is determined by summing up his performance on the criteria multiplied by these weights. Analytic hierarchy process (AHP) (Chamodrakas et al., 2010; Labib, 2011; Wang et al., 2010; Wang and Yang, 2009) and interpretive structural modelling (Mandal and Deshmukh, 1994; Kannan et al., 2009) are among the most widely used linear weighting models in supplier selection. In mathematical programming models, several suppliers are selected in order to maximise an objective function subject to supplier/buyer constraints. The objective function could be a single criterion or multiple criteria. Mathematical programming models used in supplier section include linear programming, mixed integer programming and goal programming (Ghodsypour and O'Brien, 1998; Oliveria and Lourenço, 2002; Cakravastia et al., 2002; Dahel, 2003; Yan et al., 2003; Razmi and Rafiei, 2010). Statistical approaches include methods such as cluster analysis and stochastic economic order quantity model (Mummalaneni et al., 1996; Verma and Pullman, 1998; Tracey and Tan, 2001). The unconventional supplier selection methods include cost-based models such as activity-based cost approach (Roodhooft and Konings, 1997), total cost of ownership (Degraeve et al., 2000) and transaction cost theory (Qu and Brocklehurst, 2003); neural networks (Wray et al., 1994; Albino et al., 1998; Choy et al., 2002; Lee and Ou-Yang, 2009); and fuzzy sets (Chen et al., 2006; Bevilacqua et al., 2006; Amid et al., 2006; Florez-Lopez, 2007; Büyüközkan and Çifçi, 2011).

The use of hybrid methods for supplier selection is not new. Wang et al. (2005) proposed a methodology derived from AHP and pre-emptive goal programming. Haq and Kannan (2006) developed an integrated supplier selection and multi-echelon distribution inventory framework by combining fuzzy AHP and genetic algorithm. Ramanathan (2006) proposed a data envelopment analysis (DEA) model to generate local weights of alternatives from pair-wise comparison judgment matrices used in the AHP. Sevkli et al. (2007) applied the DEA methodology developed by Ramanathan (2006) into an integrated DEA-AHP framework to select suppliers in a well-known Turkish company operating in the appliance industry. Ting and Cho (2008) used AHP, in consideration of both quantitative and qualitative criteria, to identify a set of candidate suppliers. A multi-objective linear programming model, with multiple objectives and a set of system constraints, was then formulated and solved to allocate the optimum order quantities to the candidate suppliers. Chan and Kumar (2007) and Chan et al. (2008) developed a fuzzy based AHP framework to efficiently tackle both quantitative and qualitative decision factors involved in the selection of global suppliers. They showed that fuzzy-AHP is an efficient tool for handling the fuzziness of the data involved in the global supplier selection process.

Sevkli et al. (2008) proposed a hybrid method of AHP and fuzzy linear programming for supplier selection. The weights of the various criteria, taken as local weights from a given judgment matrix, were calculated using AHP. The criteria weights were then considered as the weights of the fuzzy linear programming model. Tsai and Hung (2009) proposed a fuzzy goal programming approach that integrated activity-based costing and performance evaluation in a value-chain for optimal supplier selection and flow allocation. Sen et al. (2010) proposed a methodology that utilised a fuzzy AHP method to determine the weights of the pre-selected decision criteria, a max-min approach to maximise and minimise the supplier performances against these weighted criteria, and a non-parametric statistical test to identify an effective supplier set. Liao and Kao (2010) integrated the Taguchi loss function, AHP, and multi-choice goal programming to solve the supplier selection problem. The advantage of their proposed method was that it allowed decision makers (DMs) to set multiple aspiration levels for the decision criteria. Kuo et al. (2010) developed an integrated fuzzy AHP and fuzzy DEA for assisting organisations in supplier selection decisions. Fuzzy AHP was first applied to find the indicators' weights through expert questionnaire survey. Then, these weights were integrated with fuzzy DEA. They used α-cut set and extension principle of fuzzy set theory to simplify the fuzzy DEA as a pair of traditional DEA models. Finally, fuzzy ranking using maximising and minimising set method was utilised to rank the evaluation samples.

Amid et al. (2011) developed a weighted max-min fuzzy model to handle the vagueness of input data and different weights of criteria in supplier selection problems. They used AHP to determine the weights of criteria and the proposed model to find the appropriate order to each supplier. Büyüközkan and Çifçi (2011) developed a novel approach based on fuzzy analytic network process (ANP) within multi-person decision-making schema under incomplete preference relations. Nobar et al. (2011) developed a new conceptual supplier selection model to select preferred suppliers based on two layers or more. They solved their model with fuzzy ANP which was redesigned using a matrix manipulation method. Mafakheri et al. (2011) proposed a two-stage multiple criteria dynamic programming approach for two of the most critical tasks in supply chain management, namely, supplier selection and order allocation. In the first stage, AHP was used to address multiple decision criteria in supplier ranking. In the second stage, supplier ranks were fed into an order allocation model that aimed at maximising a utility function for the firm and minimising the total supply chain costs.

A supply chain may be defined as an integrated process wherein a number of various business entities (i.e., suppliers, manufacturers, distributors and retailers) work together in an effort to:

1 acquire raw materials

2 convert these raw materials into specified final products

3 deliver these final products to retailers.

This chain is traditionally characterised by a forward flow of materials and a backward flow of information (Shi and Xiao, 2008; Xiao and Yan, 2011). For years, researchers and practitioners have primarily investigated the various processes of the supply chain individually. Recently, however, increasing attention has been placed on the performance, design, and analysis of the supply chain as a whole. From a practical standpoint, the supply chain concept arose from a number of changes in the manufacturing environment, including the rising costs of manufacturing, the shrinking resources of manufacturing bases, shortened product life cycles, the levelling of the playing field within manufacturing, and the globalisation of market economies.

In spite of the extended research in supplier selection, Sevkli et al. (2008, p.122) have argued that "more research is definitely called for within the context of studying a more complex supply chain with multiple supply network and nodes. There is also a crucial need for investigating other hybrid methods to find the optimum supplier." In addition, most supplier selection models in the literature are intended to support DMs in the final selection phase and they have failed to consider a holistic view of the supplier selection process. Supplier evaluation and selection problems are inherently multi-criteria decision problems. Supply networks are now not only configured by suppliers, but also consist of manufacturers, retailers and customers. Therefore, a holistic and comprehensive approach for evaluating these elements in supply networks is required. We propose a multi-objective mathematical programming approach to select the most appropriate supply network elements. The process performance index (PPI) is used as an assessment tool for the supply network elements (i.e., supplier, distributor, retailer and customer) and the AHP is used to integrate the objectives of the proposed mathematical programme into a single one.

The remainder of this paper is organised as follows. In Section 2, we discuss quality control concepts and methods including the Xbar-S chart and the PPI. In Section 3, we introduce the details of the framework proposed in this study. In Section 4, we demonstrate the efficacy and applicability of the proposed methodology with a numerical example. In Section 5, we present our conclusions and future research directions.

2 Quality control

Statistical process control (SPC) charts are quality control methods that are widely used to monitor the consistency of production processes (Montgomery, 1997). When applied successfully to manufacturing processes, SPC improves product quality and productivity, and ultimately reduces production costs and increases profitability. The SPC charts are graphs of observations generated over a period of time with a centre line and control limits. Control limits are calculated from the average variation between the observations that were generated while the process was ‘in control’. A large number of observations normally fall within the control limits. However, when some observations fall on or outside the control limits, the SPC chart signals or detects a change. A signal means that there is strong possibility that the process is ‘out of control’ and an investigation may be warranted. However, not every observation that is outside the control limits deserves an investigation because an in-depth investigation is generally costly. The fundamental objective of SPC is rapid detection of real departures from the centre line without adding to the number of costly false alarms.

2.1 X-bar/S chart

There are two different methods for designing the control charts. The statistical methods which aim at achieving the best statistical performance (Lucas, 1982; Reynolds et al., 1990; Castagliola et al., 2008; Costa et al., 2009) and the economic methods which attempt to minimise the SPC cost (Duncan, 1956; Zhang et al., 2008; Torng et al., 2009; Ho and Trindade, 2009). The potential poor statistical performance is a major drawback of economic designs since the calculated cost savings may be misleading (Woodall, 1986). Consequently, the majority of the control charts used in practice is designed with statistical methods. Among them, an Xbar-S chart is a specific type of control chart that depicts the variability of average characteristics of a process over time when variables are collected in sub-groups.

The X-bar/S charts are generally employed for plotting variability of sub-groups with sizes greater than ten while the X-bar/R charts are used for plotting variability when sub-group sizes are less than ten. X-bar/S charts plot the process mean (the X-bar chart) and process standard deviation (the S chart) over time for variables *within* sub-groups.

Both the X-bar and S chart must be seen together to interpret the stability of the process. The S chart must be examined first as the control limits of the X-bar chart is determined by considering both the process spread and centre. Process variation, which is a characteristic of the spread, must be in control to correctly interpret the X-bar chart. If data-points in the S chart are outside the control limits, then the limits on the X-bar chart may be inaccurate and may falsely indicate an out-of-control condition. As in other types of control charts, data-points outside of control limits in an Xbar-S chart indicate special cases. In this paper, as suggested by Wu et al. (2011), we employ the statistical method to design the control charts, because statistical design is more realistic and used almost exclusively in today's SPC practice.

2.2 Process performance index

The PPI is an estimate of the process capability during its initial set-up, *before* it has been brought into a state of statistical control. Formally, if the upper and lower specifications of the process are *USL* and *LSL*, the estimated mean of the process is $\hat{\mu}$, and the estimated variability of the process (expressed as a standard deviation) is $\hat{\sigma}$, then the PPI is defined as:

$$\hat{P}_{pk} = \min\left[\frac{USL - \hat{\mu}}{3 \times \hat{\sigma}}, \frac{\hat{\mu} - LSL}{3 \times \hat{\sigma}}\right], \tag{1}$$

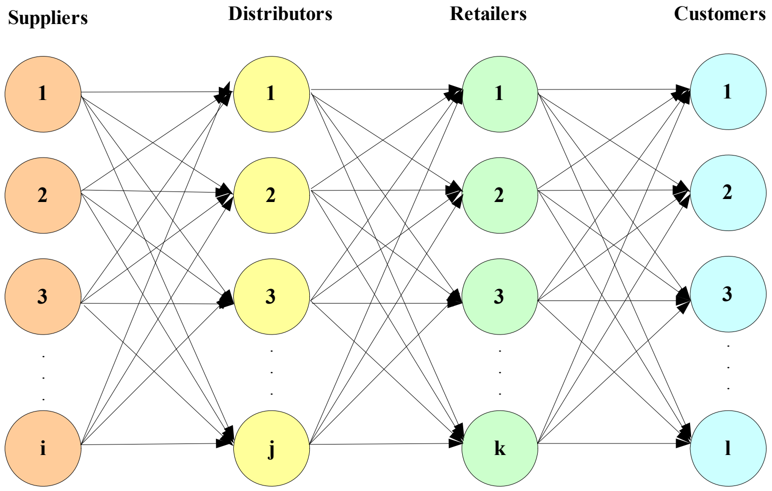
$\hat{\sigma}$ is estimated using the sample standard deviation. P_{pk} may be negative if the process mean falls outside the specification limits (because the process is producing a large proportion of defective output). Some specifications may only be one sided (for example, strength). For specifications that only have a lower limit, $\hat{P}_{p,lower} = \frac{\hat{\mu} - LSL}{3 \times \hat{\sigma}}$; for those that only have an upper limit, $\hat{P}_{p,upper} = \frac{USL - \hat{\mu}}{3 \times \hat{\sigma}}$.

Practitioners may also encounter $\hat{P}_p = \frac{USL - LSL}{6 \times \hat{\sigma}}$, a metric that does not account for process performance that is not exactly centred between the specification limits, and therefore is interpreted as what the process would be capable of achieving if it could be centred and stabilised.

3 The proposed framework

As depicted in Figure 1, a supply network can be grouped into for distinctive but inter-related layers. The first layer is a group of suppliers, the second layer is a group of distributors, the third layer is a group of retailers, and the fourth layer is a group of customers.

Figure 1 The proposed configuration of the supply network (see online version for colours)



We select a measure in each layer to represent the number of non-conformities in that level. The following measures are used in this study for the suppliers, distributors, retailers, and customers layers:

Suppliers	the cost of transportation
Distributors	the number of distribution services per month
Retailers	the number of sale services per month
Customers	the number of purchasing services per month.

Then, the X-bar/S chart is configured to determine the control area and also the outliers. In this stage, each element of our network that is out of the control limit is omitted from the evaluation. After that, we apply another criterion entitled PPI for more precise investigations. For each of the suppliers, the PPI is measured and the values are recorded. The same procedure is exerted for other layers. Now, we have the P_{pk}-based suppliers in each layer. But the problem is how to choose a set of supply network elements which are more appropriate to be included in the development plan. Here, we apply a mathematical programming to gain the collection of optimal suppliers.

3.1 The mathematical programming

Let us introduce the following mathematical notations and definitions:

i	number of suppliers;	$i = 1,2,\ldots, I.$
j	number of distributor;	$j = 1,2,\ldots, J.$
k	number of retailers;	$k = 1,2,\ldots, K.$
l	number of customers;	$l = 1, 2,\ldots, L.$
n	index of the item in layer;	$n = 1,..., N.$

m number of layers; $m = 1, 2, 3, 4.$

D_m demand of the product in layer m

O_{mn} order cost for item n in layer m

Q_{mn} expected defect rate of item n in layer m

V_{mn} capacity of item n in layer m

C_{mn} purchasing price of the product from supply network item n in layer m

W_{mn} the overall score of item n in layer m obtained from the P_{pk} process

X_{mn} total number of the product ordered to item n in layer m

$$Y_{mn} \begin{cases} 1 & \text{if an order is placed on item } n \text{ in layer } m \\ 0 & \text{otherwise} \end{cases}$$

After the weights of the supply network elements are clarified, the most appropriate one in each layer is chosen. Here, we propose the following mathematical model for supply network element selection. The weight of the items in layers as specified using P_{pk} criterion are used as significant factors for the selection.

Objective functions

Minimising total cost – the total sum of the material cost, and order cost is to be minimised:

$$\min \quad Z_1 = \sum_{n=1}^{N} \left(\sum_{m=1}^{M} C_{mn} X_{mn} + \sum_{m=1}^{M} O_{mn} Y_{mn} \right). \tag{2}$$

Minimising total defect rate – as Q_{mn} is the expected defect rate of the n^{th} item in m^{th} layer, the total defect rate to be minimised is:

$$\min \quad Z_2 = \sum_{n=1}^{N} \sum_{m=1}^{M} Q_{mn} X_{mn}. \tag{3}$$

Maximisation of total value of purchase – as W_{mn} and X_{mn} denote the normal weights of the item and the numbers of purchased units of n^{th} item in m^{th} layer, respectively, the following objective function is designed to maximise the total value of purchase:

$$\max \quad Z_3 = \sum_{n=1}^{N} \sum_{m=1}^{M} W_{mn} X_{mn}. \tag{4}$$

As illustrated above, the problem is a multi-objective one. Since the total cost and the total defect rate are independent, we can mix the first two objective functions yielding the following single cost minimisation objective:

$$\min \quad Z = \sum_{n=1}^{N} \left(\sum_{m=1}^{M} \left(C_{mn} + Q_{mn} \right) X_{mn} + \sum_{m=1}^{M} O_{mn} Y_{mn} \right). \tag{5}$$

Next, a bi-objective problem is configured to consider the third objective for maximising the total value of purchase. We apply the AHP to differentiate the significance of the objectives based on the DMs' preferences.

3.2 The AHP

AHP is a multi-attribute decision making approach that simplifies complex and ill-structured problems by arranging the decision attributes and alternatives in a hierarchical structure with the help of a series of pair-wise comparisons. Dyer and Forman (1992) describe the advantages of AHP in a group setting as follows:

1. the discussion focuses on both tangibles and intangibles, individual and shared values
2. the discussion can be focused on objectives rather than alternatives
3. the discussion can be structured so that every attribute can be considered in turn
4. the discussion continues until all relevant information has been considered and a consensus choice of the decision alternative is achieved.

Saaty (2000) argues that a DM naturally finds it easier to compare two things than to compare all things together in a list. AHP also examines the consistency of the DMs and allows for the revision of their responses (Awasthi et al., 2008). AHP has been applied to many diverse decisions because of the intuitive nature of the process and its power in resolving the complexity in a judgmental problem. A comprehensive list of the major applications of AHP, along with a description of the method and its axioms, can be found in Saaty (1994, 2000), Weiss and Rao (1987) and Zahedi (1986). AHP has proven to be a popular technique for determining weights in multi-attribute problems (Zahedi, 1986). The importance of AHP and the use of pairwise comparisons in decision making are best illustrated in the more than 1,000 references cited in Saaty (2000).

The main advantage of AHP is its ability to rank alternatives in the order of their effectiveness in meeting conflicting objectives. AHP calculations are not complex, and if the judgments made about the relative importance of the attributes have been made in good faith, then AHP calculations lead inexorably to the logical consequence of those judgments. AHP has been a controversial technique in the operations research community. Harker and Vargas (1990) show that AHP does have an axiomatic foundation, the cardinal measurement of preferences is fully represented by the eigenvector method, and the principles of hierarchical composition and rank reversal are valid. On the other hand, Dyer (1990a, 1990b) has questioned the theoretical basis underlying AHP and argues that it can lead to preference reversals based on the alternative set being analysed. In response, Saaty (1990) contends that rank reversal is a positive feature, when new reference points are introduced. AHP is based on three principles

1. constructing the hierarchy
2. priority setting
3. logical consistency.

Construction of the hierarchy

A complex decision problem, composed of multiple attributes is structured and decomposed into sub-problems (sub-objectives, criteria, alternatives, etc.), within the hierarchy.

Priority setting

The relative 'priority' given to each element in the hierarchy is determined by pair-wise comparison of the contributions of elements at a lower level in terms of the criteria (or elements) with a causal relationship (Macharis et al., 2004). In AHP, multiple paired comparisons are based on a standardised comparison scale of nine levels [see Table 1 of Saaty (1980)].

Let $C = \{C_j \mid j = 1, 2,\ldots, n\}$ be the set of criteria. The result of the pair-wise comparison on n criteria can be summarised in an $n \times n$ evaluation matrix A in which every element a_{ij} is the quotient of weights of the criteria, as shown in equation (6) below:

$$A = \left(a_{ij}\right), i, j = 1, \ldots, n. \tag{6}$$

The relative priorities are given by the right eigenvector (w) corresponding to the largest eigenvector ($\lambda_{\max}$) as:

$$Aw = \lambda_{\max} w. \tag{7}$$

When the pair-wise comparisons are completely consistent, the matrix A has rank 1 and $\lambda_{\max} = n$. In that case, weights can be obtained by normalising any of the rows or columns of A. The procedure described above is repeated for all levels of the hierarchy. In order to synthesise the various priority vectors, these vectors are weighted with regards to the global priority of the parent criteria. This process starts at the top of the hierarchy. As a result, the overall relative priorities are obtained for the elements in the lowest level of the hierarchy. These overall, relative priorities indicate the degree to which the alternatives contribute to the overall goal. These priorities represent a synthesis of the local priorities, and reflect an evaluation process that permits integration of the perspectives of the various stakeholders involved in the decision-making process (Macharis et al., 2004).

Logical consistency

A measure of consistency of the given pair-wise comparison is needed. The consistency is defined by the relation between the entries of A; that is, we say A is consistent if $a_{ij}\, a_{jk} = a_{ik}$, for each i, j, k. The consistency index (CI) is:

$$CI = \frac{\left(\lambda_{\max} - n\right)}{(n-1)}. \tag{8}$$

The final CR, calculated as the ratio of the CI and the RI, as indicated in equation (9) below, can reveal the consistency and inconsistency of the pair-wise comparisons:

$$CR = \frac{CI}{RI}. \tag{9}$$

The value *0.1* is the accepted upper limit for *CR*. If the final *CR* exceeds this value, the evaluation procedure needs to be repeated to improve consistency.

Notations and definitions

n	number of criteria	
i	number of items	
p	index for the items,	$p = 1,\ldots,P$
b	index for the sub-criteria,	$b = 1,\ldots,B$
d	index for the criteria,	$d = 1,\ldots,D$
W_{pb}	the weight of the *p-th* item with respect to the *b-th* sub-criterion	
W_{bd}	the weight of the *b-th* sub-criterion with respect to the *d-th* criterion	
R_{pd}	the weight of the *p-th* item with respect to the *d-th* criterion	
w_d	the weight of the *d-th* criterion.	

Identify the relationships and the weights of criteria with AHP

Step 1 Define the decision problem and goal.

Step 2 Structure the hierarchy from the top through the intermediate to the lowest level.

Step 3 Construct the supply network item-criteria matrix using Steps 4 to 8 using the AHP.

Steps 4 to 6 are performed for all levels in the hierarchy.

Step 4 Construct pair-wise comparison matrices for each of the lower levels with one matrix for each element in the level immediately above by using a relative scale measurement. The DM has the option of expressing his or her intensity of preference on a nine-point scale. If two criteria are of equal importance, a value of 1, signifying equal importance, is given to a comparison, while a 9 indicates an absolute importance of one criterion over the other. Table 1 shows the measurement scale defined by Saaty (1980).

Step 5 In this step, we compute the largest eigen value by the relative weights of the criteria and the sum taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy. We then analyse pair-wise comparison data using the eigen value technique. Using these pair-wise comparisons estimate the parameters. The eigenvector of the largest eigen value of matrix A constitutes the estimation of relative importance of the attributes.

Step 6 In this step, we evaluate the consistency of the judgments and perform consequence weights analysis as follows:

$$A = \left(a_{ij}\right) = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_n \\ \vdots & \vdots & \ddots & \\ w_n/w_1 & w_n/w_2 & & 1 \end{bmatrix}.$$

Note that if the matrix A is consistent (that is, $a_{ij} = a_{ik}a_{kj}$ for all $i, j, k = 1, 2,\dots, n$), then A contains no error (the weights are already known) and we have,

$$a_{ij} = \frac{w_i}{w_j}, \qquad i, j = 1, 2, \dots, n.$$

If the pair-wise comparisons do not include any inconsistencies, then $\lambda_{\max} = n$. The more consistent the comparisons are, the closer the value of computed $\lambda_{\max}$ is to n. A CI, which measures the inconsistencies of pair-wise comparisons, is set to be:

$$CI = \frac{\left(\lambda_{\max} - n\right)}{(n-1)},$$

and a consistency ratio (CR) is set to be:

$$CR = 100\left(\frac{CI}{RI}\right),$$

where n is the number of columns in A and RI is the random index, being the average of the CI obtained from a large number of randomly generated matrices. Note that RI depends on the order of the matrix, and a CR value of 10% or less is considered acceptable (Saaty, 1980).

Step 7 In this step, we configure the item-sub-criteria and the sub-criteria-criteria matrices based on the preferences of the DM. Table 1 presents the relative importance scale used in AHP. The first column is the importance score and the second column is the verbal phrase used for making the pair-wise comparisons among the item-sub-criteria in Table 2 and the sub-criteria-criteria in Table 3.

Table 1 The AHP relative importance scale

Importance score	*Verbal expression*
1	Equal
2	Weak
3	Moderate
4	Moderate plus
5	Strong
6	Strong plus
7	Very strong or demonstrated
8	Very, very strong
9	Extreme

Table 2 The network item-sub-criteria matrix

	SC_1	SC_2	...	SC_b
Item 1	$W'_{1,1}$	$W'_{1,2}$	...	$W'_{1,b}$
Item 2	$W'_{2,1}$	W'_{22}	...	$W'_{2,b}$
⋮	⋮	⋮	⋮	⋮
Item p	$W'_{p,1}$	$W'_{p,2}$	...	$W'_{p,b}$

Table 3 The sub-criteria-criteria matrix

	C_1	C_2	...	C_d
SC_1	$W_{1,1}$	$W_{1,2}$	...	$W_{1,d}$
SC_2	$W_{2,1}$	$W_{2,2}$	...	$W_{2,d}$
⋮	⋮	⋮	⋮	⋮
SC_b	$W_{b,1}$	$W_{b,2}$	...	$W_{b,d}$

Step 8 Next, we form the network item-criteria matrix as presented in Table 4.

Table 4 The supply network item-criteria matrix

	C_1	C_2	...	C_d
Item 1	R_{11}	R_{12}	...	R_{1d}
Item 2	R_{21}	R_{22}	...	R_{2d}
⋮	⋮	⋮	⋮	⋮
Item p	R_{p1}	R_{p2}	...	R_{pd}

where $R_{pd} = \sum_{b=1}^{B} W'_{pb} \times W_{bd}, \qquad \forall \ p = 1, 2, ..., P, \quad d = 1, 2, ..., D$

Step 9 We then perform a pair-wise comparison among the criteria and configure the pair-wise comparison for criteria-criteria matrix presented in Table 5:

Table 5 The criteria-criteria pair-wise comparison matrix

	C_1	C_2	...	C_d	w_d
C_1	1	a_{12}	...	a_{1d}	w_1
C_2	$1/a_{12}$	1	...	a_{2d}	w_2
⋮	⋮	⋮	⋮	⋮	⋮
C_d	$1/a_{1d}$	$1/a_{2d}$	...	1	w_d

A normalisation process is utilised to compute the w_ds presented in this table. Hence the w_ds are the criteria weights computed through the AHP.

Step 10 In this step, we calculate the overall weights of the objective functions using Tables 3 and 4, as follows:

$$\text{Total weight for function } 1 = R_{11} \times w_1 + R_{12} \times w_2 + \ldots + R_{1d} \times w_d$$

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$$\text{Total weight for function } p = R_{p1} \times w_1 + R_{p2} \times w_2 + \ldots + R_{pd} \times w_d$$

3.3 From bi-objective to mono-objective

The criteria considered here are:

- policy making
- capability to control
- strategic management.

The process is similar to the one described in Section 3.2. As a result, assuming that ψ is the weight for the cost minimisation and $\psi' = 1 - \psi$ is the weight for maximisation of total value of purchase; the following single objective function is formed:

$$\min \quad Z = \psi\left[\sum_{n=1}^{N}\left(\sum_{m=1}^{M}(C_{mn}+Q_{mn})X_{mn} + \sum_{m=1}^{M} O_{mn}Y_{mn}\right)\right] - \psi'\left[\sum_{n=1}^{N}\sum_{m=1}^{M} W_{mn}X_{mn}\right]. \tag{10}$$

Next, we identify the capacity, demand, non-negativity and binary constraints as follows:

Capacity constraints – the corresponding constraints are used since item n can provide up to V_{mn} units of the product and its order quantity in layer m (X_{mn}) should be equal or less than its capacity:

$$X_{mn} \leq V_{mn}Y_{mn}, \quad m = 1,2,\ldots,M, \quad n = 1,2,\ldots,N. \tag{11}$$

Demand constraints – the following constraints are imposed since the sum of the assigned order quantities to layer m should meet the buyer's demand:

$$\sum_{m=1}^{M} X_{mn} \geq D_m , \quad n = 1,2,\ldots,N. \tag{12}$$

Non-negativity and binary constraints – the following are the non-negativity and binary constraints imposed in the model:

$$X_{mn} \geq 0, \quad m = 1,2,\ldots,M, \quad n = 1,2,\ldots,N. \tag{13}$$

$$Y_{mn} = 0 \text{ or } 1, \quad m = 1,2,\ldots,M, \quad n = 1,2,\ldots N. \tag{14}$$

The proposed model can be applied as a decision aid tool for suppliers in a supply network. The advantages of the proposed model include the multi-objective structure helping DMs achieve multiple and conflicting objectives simultaneously, the capability to design a multi-layer model which is beneficial for the long term planning purposes.

4 Numerical illustrations

In this section, we demonstrate the efficacy and applicability of the proposed methodology with a numerical example. Consider an example with three suppliers, four distributors, five retailers and four customers. The parameter level of each of them is collected via 25 samples, separately. We applied MINITAB 14 package for simplicity in computations. Then, the X-bar/S chart is configured and analysed whether it is under control or not. If the X-bar/S chart is not under control, we revise it and reconfigure the X-bar/S chart. The same procedure is continued to construct an under control X-bar/S chart. A process performance for the parameters of the layers is shown in Figure 2. The process performance indices for each supply network element in each layer are presented in Table 6.

Figure 2 A process performance analyser (see online version for colours)

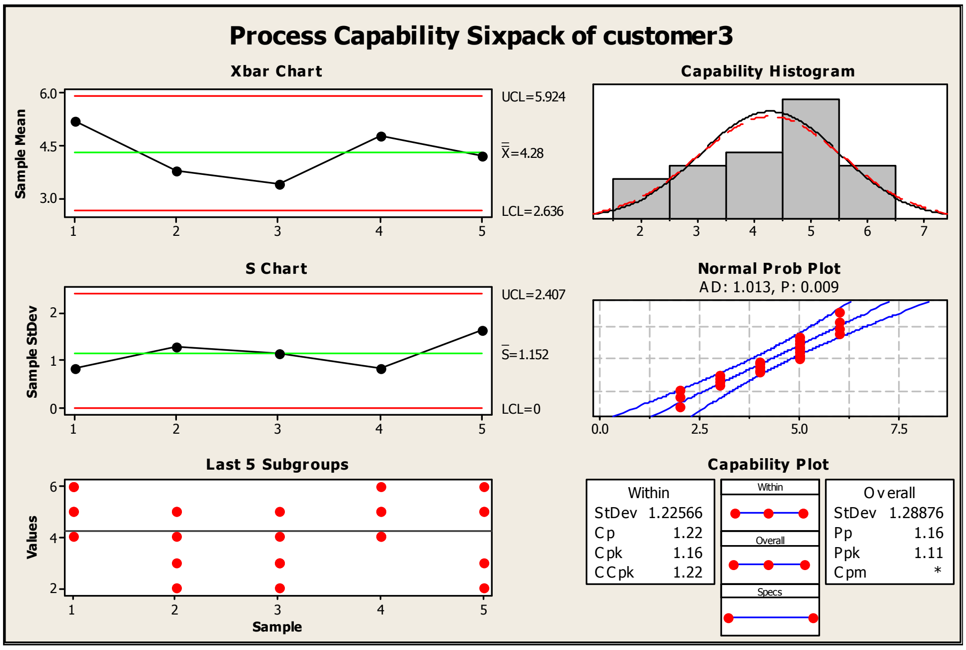

Table 6 The PPI for each supply network element in each layer

Layer	*Supplier*			*Distributor*				*Retailer*					*Customer*			
Element	*1*	*2*	*3*	*1*	*2*	*3*	*4*	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*
P_p	0.66	0.71	0.63	0.8	0.7	0.72	0.79	0.68	0.69	0.67	0.88	0.88	0.97	0.93	1.16	1.05
P_{pk}	0.57	0.58	0.41	0.7	0.62	0.69	0.71	0.65	0.65	0.62	0.88	0.7	0.83	0.89	1.11	0.92

Figure 2 presents six charts concerning the supply network. The sample mean chart in the upper-left-corner shows whether the mean for the observed samples is under control. In our example, the upper, lower and centre control limit are 5.924, 2.636 and 4.28, respectively. Also, all samples are within control limits. The sample standard deviation chart in the middle-left illustrates the same results for the standard deviation of the observed samples. The last five subgroups of the observed samples are shown in the values chart in the lower-left-corner. The capability histogram for the observed samples is shown in the upper-right-corner. This chart certifies the normality of the samples distribution. The normal probabilities are plotted in the middle-right chart. The *p*-value of this sample data set is very small showing that the distribution of the samples is normal. The capability plot and the process performance indices are all given in the last chart shown in the lower-right-corner.

Here, we need to determine the weights of the objective functions using AHP. Considering the stated criteria and applying the procedure described in Section 3.2, the following weights are computed.

$\psi = 0.468$

$\psi' = 0.532$

Some input data are required to configure the mathematical model. The capacity of each supply network element is presented in Table 7.

Table 7 The capacity of each supply network element (V_{mn})

Layer (n)	*Item (m)*				
	1	*2*	*3*	*4*	*5*
1	63	72	89	0	0
2	60	75	92	53	0
3	62	71	90	51	64
4	61	70	91	50	0

The demand for each layer is indicated in Table 8.

Table 8 The demand for each layer

Layer	*D*
1	60
2	80
3	50
4	90

The order cost, purchasing price and expected defect rate for each supplier in the corresponded time period are shown in Table 9 and Table 10. The defect rate (Q) for all supply network element in all layers is equal to 0.2.

Table 9 The order cost of each supply network item in each layer (O_{mn})

Layer (n)	*Item (m)*				
	1	*2*	*3*	*4*	*5*
1	5	4	4	0	0
2	5	5	5	3	0
3	5	5	5	4	2
4	5	5	5	2	0

Table 10 The purchasing price of each supply network item in each layer (C_{mn})

Layer (n)	*Item (m)*				
	1	*2*	*3*	*4*	*5*
1	2	2	1	0	0
2	1	4	2	5	0
3	3	6	3	2	3
4	5	3	4	4	0

Now, we solve the model using the objective function [equation (10)] along with the constraints. We used Lingo 9 to facilitate the computations. The numerical results are summarised in Table 11. Note that the objective value is 207.8606.

Table 11 The numerical values for decision variables X_{mn} and Y_{mn}

X_{mn}		*Item (m)*				
		1	*2*	*3*	*4*	*5*
Layer (n)	1	0	0	60	0	0
	2	50	0	0	0	0
	3	0	0	0	41	39
	4	0	70	20	0	0
Y_{mn}		*Item (m)*				
		1	*2*	*3*	*4*	*5*
Layer (n)	1	0	0	1	0	0
	2	1	0	0	0	0
	3	0	0	0	1	1
	4	0	1	1	0	0

As shown in Table 11, 60 units of Item 3 must be ordered in Layer 1, 50 units of Item 1 must be ordered in Layer 2. As for Layers 3 and 4, we have a split order because 41 units of Item 4 and 39 units of Item 5 must be ordered in Layer 3 and 70 units of Item 2 and 20 units of Item 3 must be ordered in Layer 4.

5 Conclusions and future research directions

Supplier selection process is one of the key operational tasks for sustainable supply chain management. In spite of the extended research in supplier selection, researchers have called for more research on:

1. complex supply chains with multiple supply network and nodes
2. hybrid supplier selection methods
3. holistic supplier selection processes.

We showed that supplier evaluation and selection problems are multi-criteria decision problems and supply networks are not only configured by suppliers, but also consist of manufacturers, retailers and customers. We proposed a holistic and comprehensive multi-objective mathematical programming approach for evaluating the supply network elements. We presented the details of the proposed supplier selection approach and used PPI as an assessment tool for the supply network elements and the AHP to combine the objectives of the proposed mathematical programme into a single one.

Although the benefits of our model are still nascent, the potential is enormous. We hope that our study can inspire others to pursue further research. It is obvious that strategic sourcing and supplier selection topics have been mainly targeted and applied to manufacturing firms producing and marketing products. We suggest that researchers explore the application of strategic sourcing and supplier selection in non-manufacturing settings to determine its applicability and overall value. In addition, little research has been done on measuring purchasing performance. It would be beneficial to explore how purchasing views itself, how it is viewed by top management, how it is viewed by internal (i.e., other functional areas within the firm) and external stakeholders (i.e., suppliers to the firm). Last, as more and more companies around the world participate in global sourcing activities, international studies should be conducted to examine supplier selection strategies and practices across different countries and cultures.

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