AN INTEGRATED FUZZY-LINEAR PROGRAMMING APPROACH FOR A SUPPLIER SELECTION PROBLEM: A CASE WITH MULTI-SOURCING AND MULTI-PRODUCT SCENARIOS

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Abstract

In today's highly competitive environment, an effective supplier selection process is very important to the success of any organization. It represents one of the most important functions to be performed by the purchasing department as a multi-criteria decision making (MCDM) problem, which is affected by quantitative and qualitative (conflicting) factors. Since there are major risks and a number of uncertainties in the decision, such as risks of not having sufficient raw materials to meet their fluctuating demand, incorporating the uncertainty of demand and supply capacity into the optimization model results in a robust selection of suppliers. In this study, the fuzzy set theory is employed due to the presence of vagueness and imprecision of information and an integrated fuzzy multi-objective linear model is introduced to deal with the problem. The proposed model integrates previous decision making approaches to compensate for any drawbacks that may exist in each approach and is capable of incorporating multiple products with multiple suppliers (sourcing). The model is then explained by an illustrative example, showing that the proposed approach, which combines total value of purchasing (TVP) to be one 1 of the objectives, as compared to the other three 3 previous approaches, can handle realistic situations better through the a sensitivity analysis. This gives insights into the robustness of the solution with respects to information vagueness related to the decision makers (DMs)' decisions.

Keywords: Supplier selection, fuzzy MCDM, multi-sourcing, multi-products, total value of purchasing (TVP)

Introduction

Supply chain management (SCM) and strategic sourcing have been one ofamong the fastest growing areas of management, particularly over the last ten 10 years. Under the expanded heading of logistics, these are now an integral part of company activity covering areas such as purchasing management, transportation management, warehouse management, and inventory management. Supplier selection decisions are complicated by the fact that

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various criteria must be considered in a decision making process. The supplier selection problem in a supply chain system is a group decision, according to multiple criteria from which a number of criteria have been considered for supplier selection in previous and present decision models (Chen-Tung *et al*., 2006). It is a multiple criteria decision making (MCDM) problem, which is affected by several conflicting factors. Consequently, purchasing managers must analyze the trade-off between these conflicting criteria. As the supplier selection problem has become one of the most important issues for establishing an effective supply chain system, they must know suitable methods and be able to select the best method based on the limitations of the buyer and suppliers as well as their purchasing strategies.

In this paper, for the first time to our knowledge, a fuzzy-linear programming multi-objective model with multi-sourcing and multi-product scenarios has been developed, in which different weights can be considered for various objectives including the total value of purchasing in relation to the remaining objectives. Two indicators, which are the weighted average of satisfaction level and minimum satisfaction level, are used to judge the superiority of the proposed model as compared to the previous ones. The paper is organized as follows: Section 2 presents the background of the problem. Section 3 addresses the fuzzy multi-objective supplier selection model and their algorithms for multi-sourcing and multi-products. Section 4 gives an illustrative example and Section 5 shows the model formulation with the results. Then, Section 6 performs the a sensitivity analysis on the imposed deterministic constraints and weight assignments. Finally, the conclusion concluding remarks are presented in Section 7.

Background of the Problem

Uncertainty of Decision Making in Manufacturing

The main disadvantage of deterministic models is their incapability of handling the randomness embedded in a real system. Similar to the problems in supplier selection, these problems often take place in a fuzzy environment. For example, demand changes occur from one 1 period to another with a probability distribution that isdifficult to estimate because of the lack of historical data. Therefore, demand must be characterized as a fuzzy variable.

Fuzzy logic (Zadeh, 1965, 1996, 1997) is an analysis method purposefully developed to incorporate uncertainty into a decision model. Fuzzy logic allows for including imperfect information no matter the cause. These characteristics have made fuzzy logic and tools associated with its use become quite popular in tackling manufacturing related challenges (Lee, 1996).

During the past two decades fuzzy linear programming has been applied to a multitude of manufacturing challenges from scheduling, aggregate planning, and material requirements planning (e.g., Chen, 2003; Mula *et al*., 2006) to supplier selection and outsourcing decisions (Bayrak *et al*., 2007; Chan *et al*., 2008; Kahraman *et al*., 2010). In practice, decision-making in supplier selection includes a high degree of fuzziness and uncertainties. Fuzzy set theory (FST) is one 1 of the effective tools to handle uncertainty and vagueness. Kumer Kumar *et al*. (2006) developed a "fuzzy multi-objective integer programing vendor selection problem" (f-MIP_VSP) model and, in the proposed model, various input parameters have been treated as vague with a linear membership function of the fuzzy type. Also, to overcome the vagueness of information, Ghodsypour and O'Brien (2001), and Amid *et al*. (2006, 2009, 2011) developed fuzzy multi-objective linear models and applied an asymmetric fuzzy decision making technique to enable the decision makers to assign different weights to various criteria.

Single vs Multiple Sourcing Supplier Selection Under Fuzzy Environment

Most supplier selection papers deal with single sourcing in which one 1 supplier can satisfy all the buyers' needs while more recent ones discussed multiple sourcing. With multiple sourcing, a buyer may purchase the same product(s) from more than one 1 supplier. If the volume is large enough, demand requirements are split among several suppliers. Having additional suppliers may alleviate the situation when the supplier's production capacity is insufficient to meet a peak demand. Multiple sourcing also motivates suppliers to be price and quality competitive.

Ghodsypour and O'Brien (2001) have stated that only a few mathematical programming models have had been published to this date that analyze supplier selection problems involving multiple sourcing with multiple criteria and with a supplier's capacity constraints. Kumar *et al*. (2004) proposed fuzzy goal programming for the supplier selection problem with multiple sourcing that included three 3 primary goals: minimizing the net cost, minimizing the net rejections, and minimizing the net late deliveries, subject to realistic constraints regarding buyer demand and vendor capacity. In their proposed model, a weightless technique is used in which there is no difference between objective functions. However, in a real situation for supplier selection, the weights of the criteria could be different and depend on purchasing strategies in a supply chain (Wang *et al*., 2004). Amid *et al*. (2006, 2009) then developed a weighted additive fuzzy model for supplier selection problems to deal with imprecise inputs and the basic problem of determining the weights of quantitative/ qualitative criteria under conditions of multiple sourcing and capacity constraints. In the weighted additive model, there is no guarantee that the achievement levels of fuzzy goals are consistent with desirable relative weights or the DM's expectation (Chen and TasiTsai, 2001 and Amid *et al*., 2006). In their later paper, a weighted max-min fuzzy multi-objective model has beenwas developed for the supplier selection problem to overcome the above problem. This fuzzy model enables the purchasing managers to not only consider the imprecise imprecision of information, but also to take the limitations of the buyer and supplier into account in calculating the order quantities from each supplier as well as matching the relative importance of the objective functions (Amid *et al*., 2011).

Single vs Multiple Materials/Products Model

Even with multiple sourcing, all the above mentioned papers usually deal with a single material (product). However, only a few papers to our knowledge have been extended to cover multiple materials under some uncertainties. In this instance, the firm could work with a number of suppliers for its raw materials. Some of the raw materials have been supplied from multiple sources while some of the others have been supplied from a single source. There have also been alternative suppliers for each raw material. Çebi and Bayraktar (2003) addressed the supplier selection problem with multiple sourcing and multiple raw materials. In their case study, within the conflicting objectives of the firm (a Turkish food manufacturing firm), which are quality maximization, late order percentage minimization, purchasing cost minimization, and also utilization maximization, 9 suppliers from 13 suppliers have beenwere proposed to get the orders. The results have been found to be consistent and reliable by the management. Jadidi *et al*. (2008) integrated the technique for order performance by similarity to ideal solution (TOPSIS) and multi-product multi-objective mixed integer linear programming to consider both tangible and intangible factors in choosing the best suppliers and defined the optimum quantities among selected suppliers under the price break. Jayaraman *et al*. (1999) proposed a mixed integer program to optimally solve the supplier selection problem by considering the number of suppliers and the possibility of combining several parts from a single supplier. Their model assumed that the organization has a certain and known demand for multiple products; these products may be raw materials or finished components. The buyers select from a potential set of suppliers to satisfy the demand and the model simultaneously determines the set of suppliers and allocates the demand among them.

Even though certain types of raw materials/ products purchased from different suppliers have been involved in these above mentioned studies, a certain degree of fuzziness and uncertainties uncertainty has not yet been introduced into the consideration. As a result, this study focuses on a fuzzy multi-objective linear model to deal with the problem. In this paper, a new model is developed that complements the weakness mentioned above and proposes a complete fuzzy multi-objective linear model approach for the supplier selection problem. In our proposed model, a fuzzy supplier selection model with multiple products/suppliers, fuzzy objective functions (goals), fuzzy constraints, and fuzzy coefficients are developed and then the developed model is converted to a single objective, step by step. The weights for the selection criteria, including the Total Value of Purchasing (TVP), can be treated as of equal or unequal importance according to the DM's preference. With the option of different weights, linguistic values expressed as trapezoidal fuzzy numbers are used to assess the weights of the factors. Similar to the Analytic Hierarchy Process (AHP) or TOPSIS approaches, new terms are presented as fuzzy positive ideal rating (FPIR) and fuzzy negative ideal rating (FNIR) to compute the weights of the factors. Then, applying he supplier constraints, goals, and weights of the factors, a fuzzy multi-objective linear model is developed to overcome the supplier selection problem and assign optimum order quantities for each supplier, for every product.

The Fuzzy Multi-Objective Supplier Selection Model for a Multi-Sourcing and Multi-Products

A general multi-objective model for the supplier selection problem for a multi-sourcing and multi-products can be stated as follows:

$$\min Z_1, Z_2, \ldots\ldots, Z_k \tag{1}$$
$$\max Z_{k+1}, Z_{k+2}, \ldots\ldots., Z_p \tag{2}$$
s.t.:
$$x \in X_d, X_d = \{x | g(x) \le b_r, r = 1, 2, \ldots.., R\} \tag{3}$$

where $Z_1, Z_2, \ldots, Z_k$ are the negative objectives or criteria such as cost, late delivery, etc., and $Z_{k+1}, Z_{k+2}, \ldots, Z_p$ are the positive objectives or criteria such as quality, on time delivery, after sale service, and so on. X_d is the set of feasible solutions, which satisfy the constraints such as buyer demand, supplier capacity, etc.

A typical linear model for supplier selection problems is min Z_1; max Z_2, Z_3 with

$$Z_1 = \sum_e \sum_i P_{e,i} X_{e,i} \tag{4}$$

$$Z_2 = \sum_e \sum_i F_{e,i} X_{e,i}, \tag{5}$$

$$Z_3 = \sum_e \sum_i S_{e,i} X_{e,i}, \tag{6}$$

s.t.:

$$\sum_i F_{e,i} \ge D_e, \tag{7}$$
$$X_{e,i} \le C_{e,i};\ i = 1, 2, \ldots, I;\ e = 1, 2, \ldots, E \tag{8}$$
$$X_{e,i} \ge 0;\ i = 1, 2, \ldots, I;\ e = 1, 2, \ldots, E \tag{9}$$

where D_e is demand of e^{th} product over period, $X_{e,i}$ = amount of product e to be purchased from supplier i, $P_{e,i}$ is per unit net purchasing cost of product e to be purchased from supplier i, $F_{e,i}$ is percentage of quality level of product e to be purchased from supplier i, $S_{e,i}$ is percentage of service level of product e to be purchased from supplier i, $C_{e,i}$ is capacity of product e to be purchased from supplier i, and I is the number of suppliers.

Three objective functions, for example, net purchasing cost (4), quality (5), and service level (6) are formulated to minimize the total monetary cost, maximize the total quality, and service the level of purchased items, respectively. Constraint (7) ensures that demand is satisfied. Constraint set (8) means that the order quantity of each supplier should be equal or less than its capacity, and constraint set (9) prohibits negative orders.

In reality, the DMs do not have exact data and complete information related to decision criteria and constraints. For supplier selection problems, the collected data do not behave crisply and they are typically fuzzy in nature. A fuzzy multi-objective model is developed to deal with the problem. Before presenting the fuzzy model, some definitions and notations should be discussed.

The Fuzzy Supplier Selection Model

In this section, first the general multi-objective model for supplier selection is presented, and then the appropriate operators for this decision-making problem are discussed.

A general linear multi-objective model can be presented as:

Find a vector x written in the transformed form $x^T = [x_1, x_2, \ldots, X_n]$ which minimizes the objective function Z_k and maximizes the objective function Z_l with

$$Z_k = \Sigma_e \Sigma_i c_{k_{e,i}} x_{e,i},\ k = 1, 2, \ldots, K \quad \text{(for negative objectives)}, \tag{10}$$

$$Z_l = \Sigma_e \Sigma_i c_{l_{e,i}} x_{e,i},\ l = p+1, p+2, \ldots, L \quad \text{(for positive objectives)}, \tag{11}$$

and constraints:

$$x_{e,i} \in x_d,\ x_d = \{x | g(x) = \Sigma_e \Sigma_i a_{r_{e,i}} x_{e,i} \leq b_r,\ r = 1, 2, \ldots, R;\ x_{e,i} \geq 0\}, \tag{12}$$

where $c_{k_{e,i}}$, $c_{l_{e,i}}$, $a_r e,i$ and b_r are crisp or fuzzy values.

Zimmermann (1987) has solved (10-12) with a single product. The fuzzy linear programing was introduced by separating every objective function Z_j into its maximum Z_j^+ and minimum Z_j^- value, as follows:

$$Z_k^+ = \max Z_k, x \in X_a, Z_k^- = \min Z_k, x \in X_d, \tag{13}$$

$$Z_l^+ = \max Z_l, x \in X_d, Z_l^- = \min Z_l, x \in X_a, \tag{14}$$

Z_k^- and Z_l^+ are obtained through solving the multi-objective problem as a single objective at a time and $x \in X_d$ means that solutions must satisfy constraints, while X_a is the set of all optimal solutions through solving as a single objective.

Since for every objective function Z_j, its value changes linearly from Z_j^- to Z_j^+, it may be considered as a fuzzy number with the linear membership function $\mu_{zj}(x)$, as shown in Figure 1.

It was shown that a linear programing problem (10-12) with a fuzzy goal and fuzzy constraints may be presented with multiple products as follows:

Find a vector x to satisfy:

$$\tilde{Z}_k = \Sigma_e \Sigma_i c_{k_{e,i}} x_{e,i} \leq \sim Z_k^0,\ k = 1, 2, \ldots, K, \tag{15}$$

$$\tilde{Z}_l = \Sigma_e \Sigma_i c_{k_{e,i}} x_{e,i} \geq \sim Z_l^0,\ l = p+1, p+2, \ldots, L \tag{16}$$

s.t.:

$$\tilde{g}_l(x) = \Sigma_e \Sigma_i a_{r_{e,i}} x_{e,i} \leq \sim b_r,\ r = 1, 2, \ldots, R \quad \text{(for fuzzy constraints)}, \tag{17}$$

$$\tilde{g}_p(x) = \Sigma_e \Sigma_i a_{r_{e,i}} x_{e,i} \leq b_p,\ p = h+1, \ldots, P \quad \text{(for deterministic constraints)}, \tag{18}$$

$$x_{e,i} \geq 0;\ i = 1, 2, \ldots, I;\ e = 1, 2, \ldots, E; \tag{19}$$

In this model, the sign ~ indicates the fuzzy environment. The symbol ≤ ~ in the constraints set denotes the fuzzified version of ≤ and has the linguistic interpretation "essentially smaller than or equal to" and the symbol ≥ ~ has the linguistic interpretation "essentially greater than or equal to". Z_k^0 and Z_l^0 are the aspiration levels that the decision-maker wants to reach.

Assuming that membership functions, based on preference or satisfaction are linear, the linear membership for minimization goals

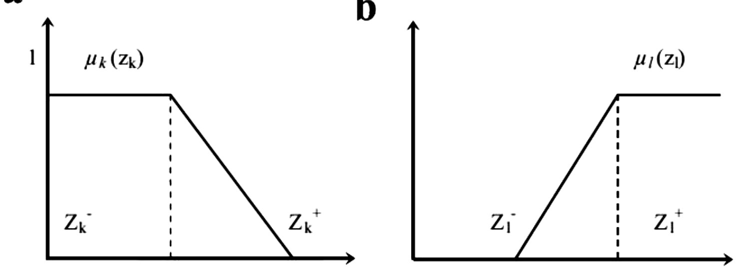

Figure 1. Objective function as fuzzy number: (a) min Z_k and (b) max Z_l

(Z_k) and maximization goals (Z_l) are given as follows:

$$\mu_{zk}(x) = \begin{cases} 1 & for\ Z_k \le Z_k^- \\ (Z_k^+ - Z_k(x))/(Z_k^+ - Z_k^-) & for\ Z_k^-(x) \le Z_k(x) \le Z_k^+,\ k = 1,2,\dots,K, \\ 0 & for\ Z_k \ge Z_k^+ \end{cases} \quad (20)$$

$$\mu_{zl}(x) = \begin{cases} 1 & for\ Z_l \ge Z_l^+ \\ (Z_l(x) - Z_l^-)/(Z_l^+ - Z_l^-) & for\ Z_l^- \le Z_l(x) \le Z_l^+, l = p+1, p+2,\dots,L, \\ 0 & for\ Z_l \le Z_l^- \end{cases} \quad (21)$$

The linear membership function for the fuzzy constraints is given as:

$$\mu_{gr}(x) = \begin{cases} 1 & for\ g_r(x) \le b_r, \\ 1 - \frac{g_r(x)-b_r}{d_r} & for\ b_r \le g_r(x) \le b_r + d_r, r = 1,2,\dots,R, \\ 0 & for\ g_r(x) \ge b_r + d_r, \end{cases} \quad (22)$$

d_r is the subjectively chosen constants expressing the limit of the admissible violation of the r^{th} inequalities constraints (tolerance interval).

Decision Making Operators

In this study, our proposed approach (integrated weighted additive with Kannan approach) has been developed and compared with three 3 previous approaches (Zimmermann, weighted additive, and weighted max-min approaches First, the max-min operator is discussed, which was used by Zimmermann (1987, 1993) to assign weights to various criteria in the Zimmermann approach. A fuzzy solution is given by the intersection of all the fuzzy sets representing either the fuzzy objective or fuzzy constraints. The solution for all fuzzy objectives and the fuzzy constraints may be given as:

$$\mu_D(x) = \{\{\cap_j \mu_{zj}(x)\} \cap \{\cap_r \mu_{g_r}(x)\}\}. \quad (23)$$

The optimal solution (x^*) is given by

$$\mu_D(x^*) = \max_{x \in X_d} \mu_D(x) = \max_{x \in X_d} \min [\min_{j=1,\dots,J} \mu_{Zj}(x), \min_{r=1,\dots,R} \mu_{g_r}(x)]. \quad (24)$$

In order to findFinding the optimal solution (x^*) in the above fuzzy model, it is equivalent to solving the following crisp model:

$$\text{Max } \lambda \quad (25)$$

s.t.:

$\lambda \le \mu_{zj}(x), j = 1, 2, \dots, J,$
(for all objective functions), (26)

$\lambda \le \mu_{g_r}(x), r = 1, 2, \dots, R,$
(for fuzzy constraints), (27)

$\lambda \in [0,1]$, and $x_i \ge 0, i = 1, 2, \dots, I.$ (28)

where $\mu_D(x)$, $\mu_{zj}(x)$, and $\mu_{g_r}(x)$ represent the membership functions of solution, objective functions, and fuzzy constraints.

Regarding this Zimmerman Aapproach, the relationship between objective functions and constraints in a fuzzy environment is fully symmetric since there is no difference between the fuzzy goals and fuzzy constraints. If the DMs decide to have unequal importance between them, the weighted additive approach can handle this problem. By multiplying each membership function of fuzzy goals by their corresponding weights and then adding the results together, a linear weighted utility function is obtained. The convex fuzzy model proposed by Bellman and Zadeh (1970), Sakawa (1993), and the weighted additive approach by Tiwari *et al.* (1987) is:

$$\mu_D(x) = \sum_j w_j \mu_{zj}(x) + \sum_r \beta_r \mu_{g_r}(x), \quad (29)$$

$$\sum_j w_j + \sum_r \beta_r = 1, \beta_r \ge 0, \quad (30)$$

where w_j and β_r are the weighting coefficients that present the relative importance among the fuzzy goals and fuzzy constraints and λ_j is the satisfaction level of the criteria. The following crisp single objective programing is equivalent to the above fuzzy model:

$$\max \Sigma_j w_j \lambda_j + \Sigma_r \beta_r \gamma_r \quad (31)$$

s.t.:

$$\lambda_j \leq \mu_{zj}(x), j = 1, 2, \ldots, J, \quad (32)$$

$$\gamma_r \leq \mu_{g_r}(x), r = 1, 2, \ldots, R, \quad (33)$$

$$\lambda_j, \gamma_{r\in} [0, 1], j = 1, 2, \ldots, J \text{ and } r = 1, 2, \ldots, R, \quad (34)$$

$$x_i \geq 0, i = 1, 2, \ldots, I. \quad (35)$$

Lin (2004) proposed a weighted max–min approach such that the ratio of the achievement level objective functions is as close to the ratio of the weight or the importance of the objectives. This model is formulated as follows:

$$\text{Max } \lambda \quad (36)$$

s.t.:

$$w_j \lambda \leq \mu_{zj}(x), j = 1, 2, \ldots, J, \quad (37)$$

$$\beta_r \gamma_r \leq \mu_{g_r}(x), r = 1, 2, \ldots, R, \quad (38)$$

More recently, Kannan *et al*. (2013) used the model based on the weighted max-min approach and added the Total Value of Purchasing (TVP) to be another objective (criterion) with its assigned weight in relation to the other objectives. They used the supplier's weights as coefficients of an objective function to allocate order quantities among the suppliers such that the TVP becomes a maximum too. w_{TVP} is then used as a given weight of the TVP in relation to the remaining objectives. In their illustrative example, they presented the case with only two 2 objectives, which are maximizing the Total Value of Purchasing (TVP) and minimizing the Ttotal Ccost of Ppurchasing (TCP) with an equal weight assignment between them (or $w_{TVP} = 0.5$).

As the Wweighted Mmax-Mmin Aapproach performed quite poorly in our preliminary experiment and as well as its results could not be obtained under a certain range of weighting allocation during the sensitivity analysis (see the results' section for the relative performance of the weighted max-min approach), the proposed new model in this study (the so called Integrated Weighted Additive with Kannan Aapproach (IAK)) is developed by integrating the Kannan's approach with the Weighted Additive Approach and weighting TVP with other objectives and fuzzy constraints (Delivery, Quality, Cost, and Demand). w_{TVP} is again used as a given weight of the TVP in relation to the remaining objectives and fuzzy constraints. By keeping the TVP as another goal, it is expected that the TVP can still become a maximum. The proposed model can then be formulated as follows:

Figure 2. Products that each supplier produces

$$\text{Max } \sum_j w_j\,(1\text{-}w_{TVP})\lambda_j + (w_{TVP})\lambda_{TVP} + \sum_r \beta_r\,(1\text{-}w_{TVP})\gamma_r \quad (39)$$

$$\lambda_j \le \mu_{zj}\,(x), j = 1, 2,\ldots, J, \quad (40)$$

$$\gamma_r \le \mu_{g_r}\,(x), r = 1, 2,\ldots, R \quad (41)$$

Illustrative Example

A company tries to select the appropriate suppliers for purchasing 4 products. At the moment, the company has three 3 suppliers (S1, S2, and S3), as shown in Figure 2, and there are three 3 decision makers (DM1, DM2, DM3) in the judging committee. The criteria for the purchasing consideration are on time delivery (C1), good quality (C2), and low cost (C3). In this problem, the demand of each product is equally set, which and ranges from 300 to 375 units, as shown in Table 1, and each supplier has a limited capacity to supply each product, as shown in Table 2, as well as a limited credit for each purchase granted by each supplier, as shown in Table 3.

Table 1. Required demand for each product

Demand (units)			
Product	**Min**	**Mode**	**Max**
1	300	325	375
2	300	325	375
3	300	325	375
4	300	325	375

Table 2. Capacity of each supplier

Maximum order quantity (units)				
Supplier	**Product**			
	1	**2**	**3**	**4**
Supplier 1	400	0	300	350
Supplier 2	350	450	0	350
Supplier 3	400	350	450	350

Table 3. Limited purchasing credit from each supplier

Limited purchasing credit amount ($)			
	Supplier 1	**Supplier 2**	**Supplier 3**
Budget	15000	15500	15000

These three decision makers use the given linguistic variables in Table 4 to assess the importance of their criteria, suppliers, and the demand constraint. Each decision maker has 7 rating levels ranging from Very Low, Low, Medium Low, Medium, Medium Good, Good, and Very Good to judge the important importance of each item. The linguistic values determined by the decision makers for evaluating among the criteria and supplier VSvs criteria are shown in Table 5 and Table 6, respectively.

Table 4. Linguistic variables for rating

Linguistic variables	Triangular fuzzy number
Very low (VL)	(0,0,2)
Low (L)	(1,2,3)
Medium Low (ML)	(2,3.5,5)
Medium (M)	(4,5,6)
Medium good (MG)	(5,6.5,8)
Good (G)	(7,8,9)
Very Good (VG)	(8,10,10)

Table 5. Importance of weights among criteria from 3 decision makers

	DM1	DM2	DM3
Delivery (C1)	VG	VG	G
Quality (C2)	G	G	G
Cost (C3)	G	MG	G
Demand	G	MG	MG

Table 6. Importance of weights of 3 suppliers vs criteria

		Delivery (C1)	Quality (C2)	Cost (C3)	Demand
DM1	S1	VG	G	F	G
	S2	G	MG	G	MG
	S3	MG	MG	VG	F
DM2	S1	G	VG	G	VG
	S2	VG	F	VG	MG
	S3	MG	F	MG	F
DM3	S1	VG	VG	MG	G
	S2	G	F	VG	MG
	S3	G	MG	VG	MG

Then, the normalized weights of each criterion and a fuzzy constraint are calculated using fuzzy TOPSIS. For the purpose of this paper, full details of fuzzy TOPSIS procedures are not presented here but more details of fuzzy TOPSIS can be seen in the past lterature, such as İrfan and Nilsen (2008); Atakan and Ali (2011) and Ahmet and Mehmet (2012). Table 7 shows the closeness coefficients and the relative normalized weights of delivery, quality, cost, and demand. Table 8 shows the normalized weighted scores of each supplier obtained from fuzzy TOPSIS such that Supplier 1 has the highest rating with the weighted score of 0.365, followed by Supplier 2 (0.33), and Supplier 3 (0.305).

Next, it is assumed that each supplier can provide different goal performances (% on time delivery, % good product quality, and unit cost), as presented in Table 9. Table 10 summarizes the data set for the membership function, which was individually optimized by the linear programming.

Table 7. Weights, distances, and coefficients of each criterion and constraint

	d^*	d^-	d^*+d^-	CC_i	Final weight
Delivery (C1)	0.79	0.06	0.85	0.929412	0.275831
Quality (C2)	0.74	0.13	0.85	0.847059	0.251391
Cost (C3)	0.68	0.17	0.86	0.802326	0.238115
Demand	0.67	0.18	0.86	0.790698	0.234664

Table 8. Weighted score and coefficients of each supplier

	CC_i	Final weighted score
Supplier 1	0.56078	0.3651474
Supplier 2	0.51275	0.3300022
Supplier 3	0.47027	0.3048504

Table 9. Suppliers' quantitative information

Delivery (%)				
	Product 1	**Product 2**	**Product 3**	**Product 4**
Supplier 1	0.80	0	0.90	0.80
Supplier 2	0.75	0.85	0	0.85
Supplier 3	0.70	0.75	0.85	0.75
Quality (%)				
Supplier 1	0.8	0	0.75	0.95
Supplier 2	0.75	0.70	0	0.8
Supplier 3	0.70	0.85	0.8	0.7
Cost ($)				
Supplier 1	20	0	25	20
Supplier 2	25	30	0	25
Supplier 3	15	20	35	25

Table 10. Data set for the membership function

Criteria & constraint	$\mu = 0$	$\mu = 1$	$\mu = 0$
Delivery	1022.50	1097.45	-
Quality	1053.75	1102.50	-
Cost	-	32120	26250
TVP	380.71	513.85	-

Model Formulations

The multi-objective linear model formulation of the illustrative example is presented. The objectives are to maximize Z_1 (Ddelivery) and Z_2 (quality) while minimize minimizing Z_3 (cost).

$$Z_1 = 0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.85X_{2,2} + 0.75X_{2,3} + 0.90X_{3,1} + 0.85X_{3,3} + 0.80X_{4,1} + 0.85X_{4,2} + 0.75X_{4,3}$$

$$Z_2 = 0.80X_{1,1} + 0.75X_{1,2} + 0.70\,X_{1,3} + 0.70X_{2,2} + 0.85X_{2,3} + 0.75X_{3,1} + 0.80X_{3,3} + 0.95X_{4,1} + 0.80X_{4,2} + 0.70X_{4,3}$$

$$Z_3 = 20X_{1,1} + 25X_{1,2} + 15X_{1,3} + 30X_{2,2} + 20X_{2,3} + 25X_{3,1} + 35X_{3,3} + 20X_{4,1} + 25X_{4,2} + 25X_{4,3}$$

s.t.:

$X_{1,1} + X_{1,2} + X1,3 \cong 325$

$X_{2,2} + X_{2,3} \cong 325$

$X_{3,1} + X_{3,3} \cong 325$

$X_{4,1} + X_{4,2} + X_{4,3} \cong 325$;

$X_{e,i} \geq 0$,

$$\mu_{z1}(x) = \begin{cases} 1 \\ (Z_1 - 1{,}022.5)/(74.95) \\ 0 \end{cases}$$

$for \quad Z_1 \geq 1{,}022.5,$
$for\ 1{,}022.5 \leq Z_1 \leq 1{,}097.45,$
$for \quad Z_1 \leq 1{,}097.45$

$$\mu_{z2}(x) = \begin{cases} 1 \\ (Z_2 - 1{,}053.75)/(48.75) \\ 0 \end{cases}$$

$for\ Z_2 \geq 1{,}102.5$
$for\ 1{,}053.75 \leq Z_2 \leq 1{,}102.5$,
$for\ Z_2 \leq 1{,}053.75$

With 4 aforementioned approaches for comparison, the formulation of each approach can be shown as follows:

Zimmermann Aapproach

Applying the membership function and the final weights, the following model formulation can be obtained.

Max λ

s.t. :

$\lambda \leq ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.85X_{2,2} + 0.75X_{2,3} + 0.90X_{3,1} + 0.85X_{3,3} + 0.80X_{4,1} + 0.85X_{4,2} + 0.75X_{4,3}) - 1{,}022.5/74.95)$

$\lambda \leq ((0.8X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.70X_{2,2} + 0.85X_{2,3} + 0.75X_{3,1} + 0.8X_{3,3} + 0.95X_{4,1} + 0.80X_{4,2} + 0.70X_{4,3}) - 1{,}053.75 / 48.75)$

$\lambda \leq (32{,}120 - (20X_{1,1} + 25X_{1,2} + 15X_{1,3} + 30X_{2,2} + 20X_{2,3} + 25X_{3,1} + 35X_{3,3} + 20X_{4,1} + 25X_{4,2} + 25X_{4,3}) / 5{,}870)$

$\lambda \leq (375 - (X_{1,1} + X_{1,2} + X_{1,3}))/50;$

$\lambda \leq ((X_{1,1} + X_{1,2} + X_{1,3}) - 300)/25;$

$\lambda \leq (375 - (X_{2,1} + X_{2,2} + X_{2,3}))/50;$

$\lambda \leq ((X_{2,1} + X_{2,2} + X_{2,3}) - 300)/25;$

$\lambda \leq (375 - (X_{3,1} + X_{3,2} + X_{3,3}))/50;$

$\lambda \leq ((X_{3,1} + X_{3,2} + X_{3,3}) - 300)/25;$

$\lambda \leq (375 - (X_{4,1} + X_{4,2} + X_{4,3}))/50;$

$\lambda \leq ((X_{4,1} + X_{4,2} + X_{4,3}) - 300)/25;$

$X_{1,1} \leq 400;\ X_{1,2} \leq 350;\ X_{1,3} \leq 400;\ X_{2,2} \leq 450;$

$X_{2,3} \leq 350;\ X_{3,1} \leq 300,\ X_{3,3} \leq 450;$

Limit capacity of each supplier

$X_{4,1} \leq 350;\ X_{4,2} \leq 350;\ X_{4,3} \leq 350$

$20X_{1,1} + 25\,X_{3,1} + 20\,X_{4,1} \leq 15{,}000$

$25X_{1,2} + 30X_{2,2} + 25X_{4,2} \leq 15{,}500$

Limit purchasing credit from each supplier

$15X_{1,3} + 20X_{2,3} + 35X_{3,3} + 25X_{4,4} \leq 15{,}000$

Weighted Aadditive Aapproach

From Table 7, the relative normalized weights of the delivery, quality, and cost objectives as well as the weight of a fuzzy constraint (demand) from fuzzy TOPSIS are presented. It was found that $w_1 = 0.276$, $w_2 = 0.251$, $w_3 = 0.238$, and $\beta_1 = 0.23$. Having applied the membership function and these final weights, the following model formulation can be obtained.

Max $0.276\lambda_1 + 0.251\lambda_2 + 0.238\lambda_3 + 0.23\gamma_r$
s.t. :

$\lambda_1 \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.85X_{2,2} + 0.75X_{2,3} + 0.90X_{3,1} + 0.85X_{3,3} + 0.80X_{4,1} + 0.85X_{4,2} + 0.75X_{4,3}) - 1{,}022.5/74.95)$

$\lambda_2 \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.70X_{2,2} + 0.85X_{2,3} + 0.75X_{3,1} + 0.80X_{3,3} + 0.95X_{4,1} + 0.80X_{4,2} + 0.70X_{4,3}) - 1{,}002.2/48.75)$

$\lambda_3 \le (32{,}120 - (20X_{1,1} + 25X_{1,2} + 15X_{1,3} + 30X_{2,2} + 20X_{2,3} + 25X_{3,1} + 35X_{3,3} + 20X_{4,1} + 25X_{4,2} + 25X_{4,3}) /5{,}870)$

$\gamma_1 \le (375 - (X_{1,1} + X_{1,2} + X_{1,3}))/50;$
$\gamma_1 \le ((X_{1,1} + X_{1,2} + X_{1,3}) - 300)/25;$
$\gamma_2 \le (375 - (X_{2,1} + X_{2,2} + X_{2,3}))/50;$
$\gamma_2 \le ((X_{2,1} + X_{2,2} + X_{2,3}) - 300)/25;$
$\gamma_3 \le (375 - (X_{3,1} + X_{3,2} + X_{3,3}))/50;$
$\gamma_3 \le ((X_{3,1} + X_{3,2} + X_{3,3}) - 300)/25;$
$\gamma_4 \le (375 - (X_{4,1} + X_{4,2} + X_{4,3}))/50;$
$\gamma_4 \le ((X_{4,1} + X_{4,2} + X_{4,3}) - 300)/25;$

Similar supplier capacity and limited purchasing credit constraints as the Zimmermann approach are applied.

Weighted Max-Min Approach

Having applied the membership function and the final weights, the following Mmax-Mmin model formulation can be obtained.

Max λ
s.t. :

$0.276\lambda \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.85X_{2,2} + 0.75X_{2,3} + 0.90X_{3,1} + 0.85X_{3,3} + 0.80X_{4,1} + 0.85X_{4,2} + 0.75X_{4,3}) - 1{,}022.5/74.95)$

$0.251\lambda \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.70X_{2,2} + 0.85X_{2,3} + 0.75X_{3,1} + 0.80X_{3,3} + 0.95X_{4,1} + 0.80X_{4,2} + 0.70X_{4,3}) - 1{,}002.2/48.75)$

$0.238\lambda \le (32{,}120 - (20X_{1,1} + 25X_{1,2} + 15X_{1,3} + 30X_{2,2} + 20X_{2,3} + 25X_{3,1} + 35X_{3,3} + 20X_{4,1} + 25X_{4,2} + 25X_{4,3}) /5{,}870)$

$0.058\,\lambda \le (375 - (X_{1,1} + X_{1,2} + X_{1,3}))/50;$
$0.058\,\lambda \le ((X_{1,1} + X_{1,2} + X_{1,3}) - 300)/25;$
$0.058\,\lambda \le (375 - (X_{2,1} + X_{2,2} + X_{2,3}))/50;$
$0.058\,\lambda \le ((X_{2,1} + X_{2,2} + X_{2,3}) - 300)/25;$
$0.058\,\lambda \le (375 - (X_{3,1} + X_{3,2} + X_{3,3}))/50;$
$0.058\,\lambda \le ((X_{3,1} + X_{3,2} + X_{3,3}) - 300)/25;$
$0.058\,\lambda \le (375 - (X_{4,1} + X_{4,2} + X_{4,3}))/50;$
$0.058\,\lambda \le ((X_{4,1} + X_{4,2} + X_{4,3}) - 300)/25;$

Similar supplier capacity and limited purchasing credit constraints as the Zimmermann approach are applied.

Integrated Weighted Additive with Kannan Approach (IAK)

Having applied the membership, the following Integrated Weighted Additive with Kannan model formulation can be obtained.

Max $0.276(1-w_{TVP})\lambda_1 + 0.251(1-w_{TVP})\lambda_2 + 0.238(1-w_{TVP})\lambda_3 + w_{TVP}\,\lambda_{TVP} + 0.23(1-w_{TVP})\gamma_r$
s.t. :

$\lambda_1 \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.85X_{2,2} + 0.75X_{2,3} + 0.90X_{3,1} + 0.85X_{3,3} + 0.80X_{4,1} + 0.85X_{4,2} + 0.75X_{4,3}) - 1{,}022.5/74.95)$

$\lambda_2 \le ((0.80X_{1,1} + 0.75X_{1,2} + 0.70X_{1,3} + 0.70X_{2,2} + 0.85X_{2,3} + 0.75X_{3,1} + 0.80X_{3,3} + 0.95X_{4,1} + 0.80X_{4,2} + 0.70X_{4,3}) - 1{,}002.2/48.75)$

$\lambda_3 \le (32{,}120 - (20X_{1,1} + 25X_{1,2} + 15X_{1,3} + 30X_{2,2} + 20X_{2,3} + 25X_{3,1} + 35X_{3,3} + 20X_{4,1} + 25X_{4,2} + 25X_{4,3})/5{,}870)$

$\lambda_{TVP} \le 0.365(X_{1,1} + X_{3,1} + X_{4,1}) + 0.33(X_{1,2} + X_{2,2} + X_{4,2}) + 0.304(X_{1,3} + X_{2,3} + X_{3,3} + X_{4,3})$

$\gamma_1 \le (375 - (X_{1,1} + X_{1,2} + X_{1,3}))/50;$
$\gamma_1 \le ((X_{1,1} + X_{1,2} + X_{1,3}) - 300)/25;$
$\gamma_2 \le (375 - (X_{2,1} + X_{2,2} + X_{2,3}))/50;$
$\gamma_2 \le ((X_{2,1} + X_{2,2} + X_{2,3}) - 300)/25;$
$\gamma_3 \le (375 - (X_{3,1} + X_{3,2} + X_{3,3}))/50;$
$\gamma_3 \le ((X_{3,1} + X_{3,2} + X_{3,3}) - 300)/25;$

$\gamma_4 \leq (375 - (X_{4,1} + X_{4,2} + X_{4,3}))/50;$
$\gamma_4 \leq ((X_{4,1} + X_{4,2} + X_{4,3}) - 300)/25;$

Similar supplier capacity and limited purchasing credit constraints as the Zimmermann Aapproach are applied. Please also note that W_{TVP} will be experimented with 4 levels ranging its in value from 0.2 to 0.8 in a step of 0.2, which is named IAKcase1 to IAKcase4, respectively.

Table 11 presents the results from each approach. Due to the fact that each approach has different settings, the obtained results are also different. For example, the weighted max-min approach recommends purchasing 324 units of Product 1 in which 290 units will be bought from Supplier 1 and 34 units from Supplier 3. As each approach provides different results, we use two 2 indicators to judge their performances, which are: (1) weighted average of satisfaction level, and (2) minimum satisfaction level. The weighted average of satisfaction level presents how close the results of that approach, in overall with their relative important weights, could achieve the maximum set goals (the maximum is 1). Then, the minimum satisfaction level presents the most minimum satisfaction levels from all goals, so that with a low satisfaction value, it shows that one 1 goal may be deserted and left to perform poorly.

Table 12 shows the relative performances from each indicator for comparison. It was found that IAKcase1 gives relatively good results from both indicators. In terms of the weighted average of the satisfaction level, IAKcase1 yields the best result while the Zimmerman Aapproach shows the best result for the minimum satisfaction level. This is as expected since the Zimmerman Aapproach does not apply weights to its goals. As a result, there is no attempt to give more or less importance to one 1 goal in particular, obtaining a low satisfaction level for that goal. For the Integrated Weighted Additive with Kannan Approach (IAK), four 4 patterns of weight assignment have been performed. It was found that applying the weight 0.2 to the TVP and 0.8 to other objectives shows the best result in this

Table 11. Recommended results from all approaches

Solution	$X_{1,1}$	$X_{1,2}$	$X_{1,3}$	$X_{2,2}$	$X_{2,3}$	$X_{3,1}$	$X_{3,3}$	$X_{4,1}$	$X_{4,2}$	$X_{4,3}$	Total units purchased
Zimmerman	0	325	0	75	249	300	25	325	0	0	1299
Additive	326	0	0	0	326	300	26	0	277	59	1314
Max-Min	290	0	34	0	325	300	35	85	239	0	1308
IAKcase1	35	0	304	0	340	300	40	340	35	0	1359
IAKcase2	280	0	45	80	245	210	115	115	210	0	1300
IAKcase3	45	0	280	264	60	210	115	65	245	14	1298
IAKcase4	146	0	178	325	0	239	85	304	21	0	1298

Table 12. Results obtained from the comparison

	Zimmerman	Additive	Max-Min	IAKcase1 $W_{TVP} = 0.2$	IAKcase2 $W_{TVP} = 0.4$	IAKcase3 $W_{TVP} = 0.6$	IAKcase4 $W_{TVP} = 0.8$
Weighted average of satisfaction level	0.77218	0.776481	0.623582	0.84648	0.76336	0.585693	0.496152
Ranking of the weighted average of satisfaction level*	3	2	5	1	4	6	7
Minimum satisfaction level	0.6667	0.475578	0.547853	0.640864	0.6	0.3999	0.2
Ranking of minimum satisfaction level*	1	5	4	2	3	6	7

* Ranking from the best (1) to the worst (7)

instance. As a result, IAKcase1 will be used to represent the IAK Approach for further comparison. When the TVP is integrated into the model's goals with a suitable weight, it was found that better results, in relation to the results from the basic weighted additive approach (which is the starting model of IAK), can be obtained. This is due to the fact that the weighted score of each supplier, which represents the overall supplier performance, is used as a part of the consideration.

Sensitivity Analysis

To give insights into the robustness of the solutions with respects to the vagueness related to the DMs' inputs, a sensitivity analysis is performed to the weighted satisfaction level on two 2 factors, which are the deterministic constraints and weight assignments to each goal.

Sensitivity Analysis on the Constraints

This sensitivity analysis is performed to examine the degree of vagueness in setting the deterministic constraints (i.e., supplier capacity and purchasing credit limitation) from each supplier. These two 2 constraints are varied up to ±30% from the base case in a step of 10%. The percentage deviations of the weighted average of the satisfaction level from the base case are plotted against the vagueness in the capacity and purchasing credit limitation to analyze such effect of the vagueness that could happen in reality.

Vagueness in Capacity

Figure 3 presents the comparison results among the studied approaches in terms of the percentage deviation of the weighted average of the satisfaction level from the base case.

Regarding the weighted average of the satisfaction level, the Zimmerman and max-min approaches are quite sensitive to the change while the weighted additive and IAK approaches are quite robust, by performing steadily with this change.

Vagueness in Purchasing Credit Limitation

Figure 4 presents the result comparisons among the studied approaches in terms of the percentage deviation of the weighted average of the satisfaction level according to the vagueness of the purchasing credit limitation.

Similar to the case of the varying capacity of each supplier, the weighted additive and IAK approaches are quite stable throughout the change of the vagueness of the purchasing credit limitation while the Zimmerman and max-min approaches are severely affected by the change.

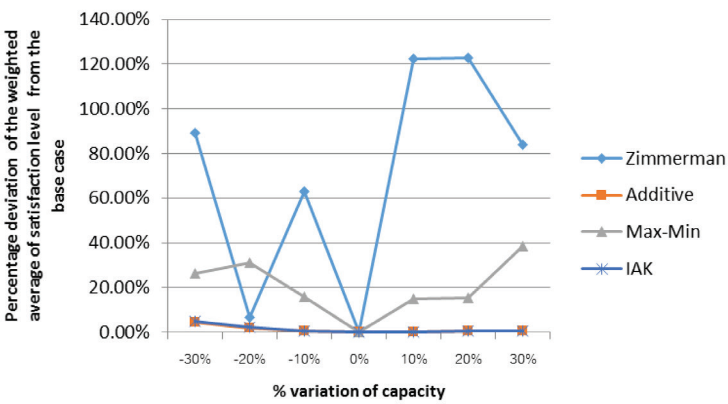

Figure 3. % deviation of the weighted average of satisfaction level of the vagueness in supplier capacity

Sensitivity Analysis on Weight Assignment

Weight assignment from a decision also plays an important role in supplier selection problems. In order to perform a sensitivity analysis on this weight assignment, 20 different cases of weight assignment are conducted. This weight assignment pattern follows the work done by Kannan *et al*. (2013). In the first four 4 cases (case 1 to case 4), the decision members' preference or ranking the delivery (criteria C1) are varied from VL to VH by maintaining the other criteria's preferences similar to the base case. Then, the next 4 cases (case 5 to case 8) vary the preference for ranking the quality (criteria C2). Similarly case 9 to case 12 are for the cost (criteria C3), and case 13 to case 16 are for the demand. Case 17 and case 18 assign VL and VG to the first two 2 criteria (delivery and quality) while case 19 and case 20 assign VL and VG to the last two 2 criteria (cost and demand). Table 13 shows the pattern of these 20 sets (cases) of weight assignment. Even though, this assignment pattern does not cover all possible combinations, it is aimed to explore a certain degree of misjudgment in evaluating the weight assignment from decision makers and the robustness of each approach to information vagueness.

Table 14 presents the results of the weighted average of the satisfaction levels and their ranking among the studied approaches. It was found that IAK can maintain the highest weighted average of the satisfaction level under the vagueness of weight assignment in most cases. For the extreme weight assignment in cases 17 and 19 where Very Low is assigned to both to the delivery and quality criteria or cost and demand criteria, its weighted average of the satisfaction level is then inferior to the other approaches. This also shows the robustness of the IAK Approach to achieve the goals set by the decision makers under the vagueness of assigning weights to these goals.

Conclusions

Supplier selection is an important strategic supply chain decision. It is always exposed to major risks and a number of uncertainties in the decision such as multiple objectives and risks of not having sufficient raw materials to

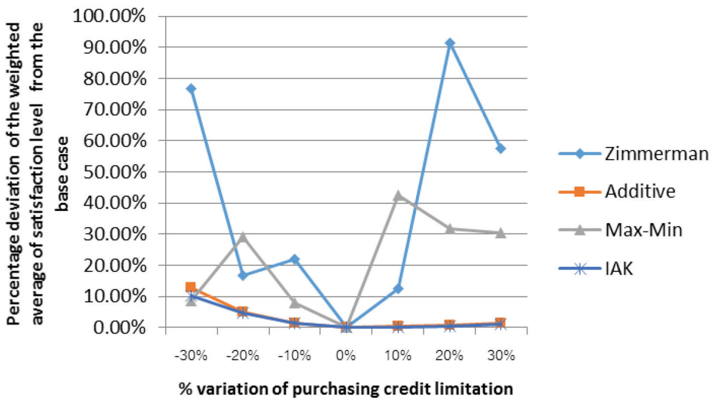

Figure 4. **% deviation of the weighted average of satisfaction level of the vagueness in purchasing credit limitation**

Table 13. Weight assignment patterns given by 3 decision makers in Case 1 – Case 20

	Case 1	**DM1**	**DM2**	**DM3**		**Case 11**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	**VL**	**VL**	**VL**	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	G	G	G		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	**MG**	**MG**	**MG**
	Demand	G	MG	MG		Demand	G	MG	MG
	Case 2	**DM1**	**DM2**	**DM3**		**Case 12**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	**ML**	**ML**	**ML**	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	G	G	G		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	**VG**	**VG**	**VG**
	Demand	G	MG	MG		Demand	G	MG	MG
	Case 3	**DM1**	**DM2**	**DM3**		**Case 13**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	**MG**	**MG**	**MG**	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	G	G	G		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	MG	G		Demand	**VL**	**VL**	**VL**
	Case 4	**DM1**	**DM2**	**DM3**		**Case 14**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	**VG**	**VG**	**VG**	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	G	G	G		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	MG	MG		Demand	**ML**	**ML**	**ML**
	Case 5	**DM1**	**DM2**	**DM3**		**Case 15**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	**VL**	**VL**	**VL**		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	MG	MG		Demand	**MG**	**MG**	**MG**
	Case 6	**DM1**	**DM2**	**DM3**		**Case 16**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	**ML**	**ML**	**ML**		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	MG	MG		Demand	**VG**	**VG**	**VG**
	Case 7	**DM1**	**DM2**	**DM3**		**Case 17**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	**VL**	**VL**	**VL**
	Quality (C2)	**MG**	**MG**	**MG**		Quality (C2)	**VL**	**VL**	**VL**
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	MG	MG		Demand	G	MG	MG
	Case 8	**DM1**	**DM2**	**DM3**		**Case 18**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	**VG**	**VG**	**VG**
	Quality (C2)	**VG**	**VG**	**VG**		Quality (C2)	**VG**	**VG**	**VG**
	Cost (C3)	G	MG	G		Cost (C3)	G	MG	G
	Demand	G	C	MG		Demand	G	MG	MG
	Case 9	**DM1**	**DM2**	**DM3**		**Case 19**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	G	G	G		Quality (C2)	G	G	G
	Cost (C3)	**VL**	**VL**	**VL**		Cost (C3)	**VL**	**VL**	**VL**
	Demand	G	MG	MG		Demand	**VL**	**VL**	**VL**
	Case 10	**DM1**	**DM2**	**DM3**		**Case 20**	**DM1**	**DM2**	**DM3**
Criteria	Delivery (C1)	VG	VG	G	Criteria	Delivery (C1)	VG	VG	G
	Quality (C2)	**ML**	**ML**	**ML**		Quality (C2)	G	G	G
	Cost (C3)	G	MG	G		Cost (C3)	**VG**	**VG**	**VG**
	Demand	G	MG	MG		Demand	**VG**	**VG**	**VG**

meet their fluctuating demand. In this paper, multi-sourcing multi-product supplier selection was presented. Integrating the fuzzy TOPSIS and fuzzy linear model programming for choosing suppliers among conflicting objectives (that which are quick delivery, good quality, but low cost) was able to accomplish the task. In this model, the fuzzy TOPSIS was used first to calculate the weights of the criteria and weighted scores of suppliers, and then fuzzy linear programming was used to find out the optimum solution of the problem. Vagueness and imprecision could also be effectively handled in this model. In a practical situation, all objective functions do not possess the same weight. Therefore, the weights of the objective functions must be able to change according to the requirement of the DMs. These assigned weights can be easily calculated by using the fuzzy TOPSIS method. The supplier selection problem under multiple sourcing and multiple product scenarios could be even more complicated since the consideration of weight assignment is required, not only among criteria VS vs suppliers, but among different products as well. However, this could be successfully incorporated in this study.

In addition, an illustrative example was used to demonstrate the implication of the proposed approach for supplier selection. It was found that the new proposed algorithm, the Integrated Weighted Additive with Kannan ApproachIAK, could outperform other approaches in most performance measures, and performed best under the sensitivity analysis, showing its robustness on the degree of vagueness in the demand and two 2 imposed deterministic constraints (capacity and purchasing credit

Table 14. Results obtained from comparison of the weighted average of satisfaction level

(Ranking from the best (1) to the worst (4))

	Zimmerman	Additive	Max-Min	IAK
Case 1	0.777498 (3)	0.822727 (1)	N/A*	0.822727 (1)
Case 2	0.754565 (3)	0.778845 (2)	0.32166 (4)	0.865691 (1)
Case 3	0.754565 (3)	0.778845 (2)	0.32166 (4)	0.865691 (1)
Case 4	0.751698 (3)	0.77336 (2)	0.605692 (4)	0.863122 (1)
Case 5	0.780478 (2)	0.699608 (3)	N/A*	0.818413 (1)
Case 6	0.753511 (3)	0.770785 (2)	0.245082 (4)	0.770785 (1)
Case 7	0.756147 (3)	0.763827 (2)	0.242403 (4)	0.861439 (1)
Case 8	0.750118 (3)	0.779739 (2)	0.611537 (4)	0.866852 (1)
Case 9	0.775254 (3)	0.998104 (2)	N/A*	1 (1)
Case 10	0.753266 (3)	0.777469 (2)	0.490646 (4)	0.862415 (1)
Case 11	0.755415 (3)	0.78864 (2)	0.48891 (4)	0.861287 (1)
Case 12	0.750499 (3)	0.773694 (2)	0.24815 (4)	0.862415 (1)
Case 13	0.682454 (3)	0.784995 (2)	N/A*	0.802764 (1)
Case 14	0.751429 (3)	0.774479 (2)	0.481658 (4)	0.793541 (1)
Case 15	0.744159 (3)	0.776318 (2)	0.254609 (4)	0.793541 (1)
Case 16	0.760793 (3)	0.780413 (2)	0.463063 (4)	0.792376 (1)
Case 17	0.834305 (2)	1 (1)	N/A*	0.786322 (3)
Case 18	0.749658 (3)	0.778796 (2)	0.500317 (4)	0.794017 (1)
Case 19	0.674833(3)	1 (1)	N/A*	0.813809 (2)
Case 20	0.752503 (3)	0.776812 (2)	0.622423 (4)	0.794017 (1)

* These values cannot be calculated since with the Max-Min Approach when all DMs assign the weight of one objective (w_j) to be very low, the objective function's value, which is Max λ, would be 0. As a result, the calculated values of weighted average satisfaction level are misleading.

limitation). When the TVP was integrated into the model's goals with a suitable weight, better results could be obtained. This is due to the fact that the weighted score of each supplier, which represents overall supplier performance, is used as a part of the consideration.

However, further analysis may be required to find out more outcomes and explore other kinds of comparisons. Due to the complex procedures of the proposed approach, a decision support tool developed in Excel with its solver was also built to accommodate such complex processes and make the decision processes easier for the DMs. This is a very useful decision making tool for mitigating buying challenges but more user friendly interfaces are still required to make the tool more appealing to users. The tool also needs to be extended for solving larger scale problems.

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