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This work presents a linear programming model with fuzzy multiple goals for analysing cost effectiveness during vendor selection. The proposed model considers material preparation for outsourcing firms, technological transition, quality, lead time, and their interactions. The model also uses cost, quality and effectiveness as decision criteria for capacity planning and for determining product requirements for multi-stage planning of the make/outsourcing formulation. Different scenarios involving capacity transitions limited by technical factors, additions, and support shortages are mathematically formulated. In addition to its functions for evaluating cost minimisation and for accommodating the components of lead time, quality, and responsiveness, the proposed model also integrates multi-stage functions for supply chain systems. Therefore, the analytical results of this study, regardless of application outcomes or analysis methodology, provide decision criteria for manufacturing firms and introduce a new area of academic research.

Keywords: vendor selection; integrated multi-stage model; outsourcing; cost effectiveness

1. Introduction

As international division has strengthened, and information network systems become an important means of global logistics, flexibility is critical for most production systems. Globalisation and technological innovation are common denominators of these marketing and corporate business challenges (Momme 2002). Outsourcing is a major strategic option because it enables firms to narrow production activities and focus on core competencies (Gules and Burgess 1996, Spekman *et al.* 1999). Outsourcing refers to ongoing purchases of goods or services, often from a subsidiary company (Linder 2004). Outsourcing has become an important business approach because it can achieve competitive advantages when products or services are produced more effectively and efficiently by outside vendors (Yang *et al.* 2007). Yang *et al.* also noted that outsourcing is not purely a make-or-buy decision; it involves a switch from internal production to external procurement.

To maintain competitiveness, outsourcing must achieve cost, quality and production efficiency in the supply chain systems. The need to consider outsourcing opportunities

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forces firms to assess their effectiveness. An effectiveness analysis of outsourcing possibilities must elucidate the requirements and evaluation strategies of vendors.

In the real world, potential vendors must be evaluated and selected in a prior evaluation phase. Quality performance is an initial consideration and experiences are used as guidelines for selecting potential vendors. Related information includes costs, defect percentages, lateness deliveries, etc. This is particularly important for high-tech firms.

Recent outsourcing studies can be distinguished from multiple perspectives. Analyses from the perspective of production planning examine cost-effectiveness of retaining core competencies and releasing other operations to outside manufacturers or to regions with cheaper labour. However, firms may also outsource core competencies to maintain cost advantages and flexibility. This observation implies that maintaining a make/buy ratio at a certain level and reviewing core competence are ongoing processes. Hence, a workable outsourcing strategy requires a scheme for evaluating capacity planning and outsourcing decisions.

Numerous outsourcing studies have proposed methods of improving flexibility (Chalos 1995, Company and Ronen 2000, Platts *et al*. 2002). Although these studies have improved understanding of how outsourcing impacts the conceptual phase, systematic studies are still needed to analyse how outsourcing impacts cost effectiveness, component costs, capacity and production planning. Moreover, the decision process for make/buy strategies requires further investigation (Tayles and Drury 2001). Specifically, the relationship between capacity planning and outsourcing strategy has been inadequately explained from a flexibility perspective.

The outsourcing decision problem is closely related to the interdependence of cost-effectiveness among alternatives (Bendor *et al*. 1985, Pan 1989). However, a linear programming model with fuzzy multiple goals for analysing cost-effectiveness of vendor selection has not been developed.

This study focuses on outsourcing cost-effectiveness. An optimal model is systematically formulated to analyse outsourcing strategies given varying cost, quality and due dates. The proposed optimisation model with fuzzy multiple goals evaluates outsourcing options. Alternatives considered in the proposed models are materials preparation for outsourcing firms, make/outsourcing decisions, and quality and operations limitations. The model considers capacity planning and product requirements with multi-stage planning in terms of connecting relationships to outsourcing firms as a basis of model formulation. To construct model criteria, this analysis examines various components such as cost, quality, satisfaction, lead time, transaction cost and effectiveness in the form of decision alternatives.

The remainder of this paper is organised as follows. A literature review is given in Section 2. Section 3 then formulates the outsourcing cost-effectiveness problem as a linear programming model with fuzzy multiple goals. Next, Section 4 demonstrates the applicability of the proposed determining methodology in a case of a power supply firm. Conclusions are finally drawn in Section 5, along with recommendations for future research.

2. Literature review

Although vendor selection is a decision making problem, some studies analyse it as a strategic decision making problem (Fisher 1997, Huang *et al*. 2002, Davidrajuh 2003, Sucky 2007). Outsourcing studies are remarkably numerous and diverse. Some of the many aspects of vendor selection problems are described in the following subsections.

2.1 *Conceptual development*

Firms tend to allocate their resources to their core activities. One reason for outsourcing is the availability of cheaper labour in less developed regions or countries. An analysis of international outsourcing by Long (2005) presented a model for explaining incomplete outsourcing in the presence of spillover and concluded that firms must appropriately balance marginal gains with marginal costs. Swenson (2004) discussed the problem of capital intensity in overseas assembly and concluded that low-capital-intensity industries are more likely to respond to cost changes than are high-capital-intensity industries. Thus, capital intensive firms require highly specific matches that may be difficult to locate. In a study of contract manufacturers, Kim (2003) proposed a model for comparing two different manufacturing arrangements in terms of part consignment and turnkey arrangement. Problems presented in the proposed model were the proportion of outsourcing to each contract manufacturer and how processed the semi-finished units should be when they are returned by the contract manufacturers.

Globalisation now allows vendors to access worldwide markets through complex multi-layer supply chains. Abdel-Malek *et al.* (2005) developed a performance measure for multi-layer supply chains and outsourcing strategies, particularly in long-term partnerships.

The importance of vendor selection and delivery increases as outsourcing activity intensifies (Ernst *et al.* 2007). Aissaoui *et al.* (2007) identified six major purchasing decision processes: (1) make or buy; (2) vendor selection; (3) contract negotiation; (4) design collaboration; (5) procurement; and (6) sourcing analysis. Vendor selection criteria may be objective or subjective. However, drawbacks are that the vendor offering the lowest price may not deliver the best quality, or the vendor with the best quality may not deliver on time. Therefore, as Robinson (1968) indicated, a trade-off mechanism is needed to resolve conflicting goals.

Although the quantitative method of vendor selection has received much attention, many studies argue that qualitative thinking in terms of outsourcing strategy is more important. Huang and Keskar (2007) noted that an optimal mathematical solution is meaningless if it is inconsistent with the business strategy of a firm while strategic thinking cannot provide quantitative solutions. To solve the problem of appropriate order allocation to vendors, Karpak *et al.* (1999) formulated a goal programming model to minimise costs and maximise delivery reliability and quality in vendor selection. Regarding total costs, Degraeve and Roodhooft (2000) addressed the vendor selection problem with activity-based cost information using a mathematical programming approach. However, Amid *et al.* (2006) noted that these deterministic models are inadequate for solving vendor selection because they do not consider the vagueness of parameters.

As for vendor selection, an optimisation approach is useful for achieving the specific criteria of a given situation. An optimisation model for vendor selection under varying conditions would simplify vendor selection and order allocation. However, some studies argue that vendor selection has quantitative and qualitative limitations of vendor selection (Ghodsypour and O'Brien 1998, Wang *et al.* 2004).

Humphreys *et al.* (2007) presented a process for evaluating potential vendors from the product development perspective during the design phase. The major issues addressed were development specifications, interchangeable parts, part standardisation and simplification, part substitution and part exclusions. Moreover, the following four distinctive indices were used to evaluate vendors: satisfaction index, flexibility index, risk index, and confidence index.

Vendor selection based on accumulated experience is rarely effective or scientific due to the reliance on subjective judgment and lack of systematic analysis. Choy *et al.* (2002) proposed an intelligent vendor management method for vendor selection that included a function for continuous tracking and benchmarking. The proposed method was a case-based reasoning and neural network.

2.2 *Mathematical programming methods*

2.2.1 *Analytic hierarchy process*

When selecting from outsourcing alternatives, the main objective is minimising total costs under various constraints. Total costs include expenditures for the goods themselves and the associated costs of the outsourcing transaction (Tsai and Lai 2007). Total cost items considered in outsourcing decisions included fixed costs, variable costs and related material supply costs, and transportation costs. The analytic hierarchy process (AHP) can often solve outsourcing problems by constructing an outsourcing framework and mathematical models.

The AHP method developed by Saaty (1980) has been used extensively to analyse both quantitative and qualitative measures. Applying AHP usually starts from a strategic phase and then develops a decision-making algorithm or model. Korpela *et al.* (2002) proposed an AHP and mixed integer programming (MIP) for solving the production allocation problems of vendors by maximising both the strategic importance of customers and preferences of customers while minimising their risks. Lin and Chang (2008) presented a fuzzy approach for buyer evaluation when orders exceed production capacity.

The AHP is a simple but effective approach for devising an intricate, multiple factor, and multiple-attribute problem for analysing hierarchical levels. Liu and Hai (2005) proposed a three-level hierarchy for ranking and selecting vendors by comparing quality, flexibility, delivery and costs.

Gencer and Gürpinar (2007) constructed an analytic network process for solving the vendor selection problem in an electronics firm. The proposed approach included six steps: analysing the vendor selection problem; determining goal and vendor selection criteria; selecting alternative vendors; building the vendor selection model; making paired comparisons; and developing the solution algorithm and making the final decision.

Ramanathan and Ganesh (1995) and Oeltjenbruns *et al.* (1995) applied AHP and linear programming (LP) to solve resource allocation and equipment replacement problems. Several studies have also employed AHP to evaluate business performance from varying outsourcing perspectives (Chan and Lynn 1991, Lee *et al.* 1995, Rangone 1996). Hafeez *et al.* (2002) provided a methodology for determining capacity by using an AHP approach with a balanced score card of financial and non-financial performance measures based on quantitative and qualitative data. Hafeez *et al.* (2007) subsequently proposed a structural framework for evaluating firm assets and competence using a two-stage AHP. Sucky (2007) noted that current vendor selection approaches do not consider the time interdependencies associated with the costs of selecting and then switching to a new vendor. Ghodsypour and O'Brien (1998) utilised AHP and LP to develop a decision support system for solving vendor selection problems. Mohanty and Deshmukh (1993), Bhutta and Huq (2002), Handfield *et al.* (2002), and Wang and Yang (2007) have published similar works.

The many applications of AHP include vendor selection, resource allocation, equipment replacement and capacity planning. However, the disadvantage of AHP is its reliance on a pairwise method for evaluating alternatives and its inability to give a precise value for decision making.

Optimisation is a conventional means of solving outsourcing decision problems. Methods used to solve related outsourcing decisions can be classified as linear programming/mixed integer programming (LP/MIP), multiple goal programming (MGP) and fuzzy multiple goal programming (FMGP).

2.2.2 *LP/MIP*

The LP and MIP are used to solve vendor selection problems in outsourcing problems, and reducing costs is the core goal of model formulation. Other commonly formulated goals are reducing total costs, purchasing costs and inventory holding costs. Several studies have examined various aspects of cost assessment in different environments. An early work by Wind and Robinson (1968) developed an LP model of performance measurement as vendor determinants. Moore and Fearson (1973) proposed an LP model with price, quality and delivery factors for solving the vendor selection problem. To enhance cost-effectiveness, Pan (1989) developed an LP model to address the problem of aggregate price under constraints of service level, lead time and quality. Bendor *et al.* (1985) proposed an MIP model of cost-effectiveness for minimising purchasing, inventory and logistics costs.

Gaballa (1974) developed an MIP model for minimising the total discounted price of allocated items to vendors given the constraints of vendor capacity and demand satisfaction.

2.2.3 *Multiple criteria*

Vendor selection, a multi-criterion problem, includes both tangible and intangible factors. Demirtas and Ustun (2008), and Ustun and Demirtas (2008) presented an integrated multi-objective decision making process for vendor selection, which included order selection and multi-period lot-sizing problems. A workable algorithm for optimising a solution must have a sufficiently rich rating index for each alternative to enable effective decision making. Using multiple criteria optimisation requires a trade-off among the various criteria that may be indiscernible in a single objective model. The vendor selection problem is basically a multi-criteria problem, but multi-criteria techniques are rarely used to solve the problem (Wadhwa and Ravindran 2007). From the managerial perspective, a large set of performance criteria must be identified (Weber and Current 1993) and suitably weighted according to their context-specific importance (Dulmin and Mininno 2003).

Chen *et al.* (2006) treated quantitative and qualitative factors of quality, price and delivery performance in terms of linguistic values as the ratings and weights for constructing a hierarchical multi-criteria decision making model.

Conventional vendor evaluation methods that emphasise strategic importance have recently incorporated multi-vendor criteria into the evaluation process (Chapman 1989, DeBoer *et al.* 1998, Humphreys *et al.* 2007). Decision variables such as price, delivery, performance and quality have been incorporated. Talluri and Narasimhan (2003) noted that no studies have proposed performance variability measures for the selection process. They therefore proposed a max-min productivity method to optimise the decision-making process.

Ghodsypour and O'Brien (1998, 2001) proposed a vendor selection approach given conditions of multiple sourcing, multiple criteria and capacity constraints. The approach developed a single objective model and a multiple objective programming model to minimise total logistic costs, including aggregate price, ordering costs and inventory costs, given the capacity constraints of vendors and the budget, quality and delivery constraints of buyers.

A multi-criteria model was developed by Weber and Current (1993) to analyse the trade-offs between the conflicting goals of price, quality and delivery performance which performs a trade-off analysis of conflicting goals. Chaudhry *et al.* (1993), Weber *et al.* (2000), and Bhutta and Huq (2002), have developed similar models.

2.2.4 *Fuzzy multiple goal programming*

In reality, factors or parameters formulated in the model are uncertain and cannot be precisely estimated. Fuzzy goal programming (FGP) was developed to rectify this research gap. Fuzzy set theory is widely used for formulating problems with insufficient information related to different criteria in real-world decision making. Fuzzy set theory was initially developed by Zadeh (1965) and later refined by Bellman and Zadeh (1970) to solve decision problems with uncertain characteristics. Zimmermann (1978) then summarised the implementation concept of multiple goal programming and used the linear membership function to represent and integrate each fuzzy goal, and then to convert the problem into an LP computable presence.

Fuzzy multiple goal programming (FMGP) has been applied in various fields. For instance, Slowinski (1986), Chiampi *et al.* (1996), and Teng and Tzeng (1996) used FMGP to analyse water pipeline systems, magnetics planning, and transportation projects, respectively. Compared to AHP or multiple criteria optimisation, FMGP analyses of outsourcing problems are rare, a literature review reveals only two examples: Kumar *et al.* (2004, 2006) and Araz *et al.* (2007). Amid *et al.* (2006) demonstrated a fuzzy multi-objective model with different weights for solving the vendor selection problem given imprecise information about cost, quality, delivery and service.

In actual production, firms must invest substantial time and capital to configure part changes. After analysing actual cases, Wang (2008) proposed a quantification model for assessing configuration changes in engineering products with complex structure by observing actual cases. The model was used for configuration changes given parts quality, delivery time, cost and fuzziness attributes. Wang and Che (2007) used a genetic algorithm and fuzzy theory to develop an optimisation algorithm for vendor selection given specific configuration changes with cost and quality attribute factors.

2.3 *Summary of literature review*

Although the outsourcing problem has received considerable attention, none of the models proposed in the literature has integrated multiple goals with flexibility and alternative analyses or responses in the literature are often confusing. The outsourcing decision problem is related to the interdependence of cost-effectiveness among alternatives. Individual optima may not ensure the global optima.

Moreover, some studies mention that the outsourcing decision is a matter of capacity extension of make/buy decision with various factors. However, models integrating make/outsourcing factors with vendors are rare. Several unresolved problems are the following:

(1) The literature confirms that capacity planning is vital in outsourcing decisions. However, many studies of vendor selection have focused on the shortcoming of supply chain systems without systematic formulations.
(2) Flexibility is a core outsourcing advantage, and imprecision is an important variable requiring formulation. Most proposed models have been multi-criteria or deterministic models. However, a model combining multi-criteria and uncertainty is required.
(3) Previous models were incomplete. For instance, no models have integrated such factors as lead time, purchasing discount, lateness and quality.
(4) Current models for formulating multiple materials with multiple vendors in multiple periods are inadequate.

This work proposes a linear programming model with fuzzy multiple goals for improving the aforementioned problems. The proposed formulation of outsourcing decisions regarding cost-effectiveness in a linear programming model with fuzzy multiple goals is unique in the literature. The model can evaluate a set of options for outsourcing decisions.

3. The proposed model

Symbols

i : sources: $i=0$ if manufacturing option is selected, otherwise outsourcing options are selected;
j : items, $j=1, 2, \ldots, J$;
S_{ij} : $S_{ij}=1$ if make option i selected for item j; 0 otherwise;
X_{ij} : amount of item j provided by source i; $i=0$, if make option is selected;
β_j : additional cost of supply materials to outsourcing firms for item j;
α_j : cost of technological transition to outsourcing firms for item j;
E_j : cost of technological transition for item j, in dollars ($);
D_j : demand for item j (normal distribution);
f_j : fixed cost of make option for item j, in dollars ($);
L_{ij} : lead time for item j outsourced by option i;
L_i : maximum lead time allowed for item j;
G_{ij} : minimum accepted order quantity of item j manufactured by option i;
k_{ij} : quality level for item j manufactured by option i, as a percentage;
c_{ij} : unit cost of item j outsourced by option i, $i\neq 0$;
b_j : unit loss of defects for item j;
m_j : unit material cost for item j, $/unit;
v_j : unit variable cost of manufacturing option for item j, $/unit;
H_{ij} : upper capacity limit for item j manufactured by option i;
w_j : weight of goal.

Outsourcing not only compensates for limited capacity, it also enhances competitiveness by reducing fixed costs and minimising capacity investment. In practice, firms must balance the marginal gain (cost saving) of outsourcing an additional unit with the marginal cost of doing so (reducing cost to rivals). As such, a corporation contemplating outsourcing must consider strategic changes as well as cost saving (Long 2005). Practically, maintaining quality and efficiency are vital for a feasible outsourcing agreement. To achieve the desired level of outsourcing quality, a corporation must at least confirm that the firms performing the outsourced manufacturing have the required technology and material components. Thus, the outsourced firm may need technology transition, materials preparation or both. Given technology transition and material preparation, various scenarios analysed in the proposed model are described below.

Decision cases:

- Case 1: total make
  In the case of total make, total costs include fixed cost and variable costs as follows:

$$\sum_{j=1}^{J} f_j S_{ij} + \sum_{j=1}^{J} v_j X_{0j}.$$

- Case 2: make with outsourcing
  In the case of make with outsourcing, the costs in sum consist of the case of make with fixed and variable costs, outsourcing costs, and quality costs as follows:

$$\sum_{j=1}^{J} f_j S_{ij} + \sum_{j=1}^{J} v_j X_{0j} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij} + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \left(1 + k_{ij}\right).$$

- Case 3: outsourcing with technological transition
  This scenario represents the case in which outsourcing firms lack specific technologies. In this case, total costs include Case 2 with additional transition costs. However, a return from the outsourcing firm in terms of discount is required:

$$\sum_{j=1}^{J} f_j S_{0j} + \sum_{j=1}^{J} v_j X_{0j} + \sum_{i=1}^{I}\sum_{j=1}^{J} E_j S_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij}\left(1 + \alpha_j S_{ij}\right) + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \left(1 + k_{ij}\right).$$

- Case 4: outsourcing with material preparation
  This scenario represents the situation in which a material is unique or material quality is assured. In this case, total costs include Case 3 with additional quality costs and material supply costs. However, the required material discount deducted from the outsourcing firm is as follows:

$$\sum_{j=1}^{J} f_j S_{0j} + \sum_{j=1}^{J} v_j X_{0j} + \sum_{i=1}^{I}\sum_{j=1}^{J} m_j X_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij}\left(1 + \beta_j S_{ij}\right) + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \left(1 + k_{ij}\right).$$

- Case 5: outsourcing with technological transition and material preparation
  In this scenario combining Cases 3 and 4, costs are calculated as follows:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} E_j S_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} m_j S_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij}\left(1 + (\alpha_j + \beta_j) S_{ij}\right) + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \left(1 + k_{ij}\right). \quad (1)$$

The objective function:

$$\begin{aligned}\min Z = & \sum_{j=1}^{J} f_j S_{0j} + \sum_{j=1}^{J} v_j X_{0j} + \sum_{i=1}^{I}\sum_{j=1}^{J} E_j S_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} m_j S_{ij} \\ & + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij}\big(1 + (\alpha_j + \beta_j) S_{ij}\big) + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \big(1 + k_{ij}\big).\end{aligned} \tag{2}$$

Constraints:

$$\sum_{i=0}^{I} X_{ij}(1 - k_{ij}) \geq D_j \tag{3}$$

$$G_{ij} S_{ij} \leq X_{ij} \leq H_{ij} \tag{4}$$

$$L_{ij} S_{ij} \leq L_i \tag{5}$$

$$X_j \geq X_{ij} \tag{6}$$

$$S_{i+1j} - S_{ij} \leq 0 \tag{7}$$

$$S_{ij} + S_{i+1j} \leq 1 \tag{8}$$

$$X_{ij} \geq 0 \tag{9}$$

$$0 \leq \alpha_j \leq 1 \quad \text{and} \quad 0 \leq \beta_j \leq 1. \tag{10}$$

Equations (3) to (5) represent the constraints for the requirements of demand, capacity, quality, and due date. Specifically, Equation (3) depicts the requirements for satisfying individual items. Equation (4) ensures an order exceeds the minimum required quantity but not the capacity of the outsourcing firm. Equations (5) and (6) ensure that product quality and due date satisfy the provision settings. Equations (7) and (8) represent the constraints on selecting outsourcing firms. Specifically, Equation (8) ensures that only a firm is selected and supplied with materials, and Equation (7) regulates the sequence of outsourcing firms. Equations (9) and (10) are non-negative constraints.

3.1 *The multiple objective linear model*

In this section, a multiple objective linear programming model (MOLP) is formulated to estimate the cost-effectiveness of an outsourcing program. Three objectives are minimising costs, minimising defects, and minimising late deliveries:

- Cost minimisation: the original objective function in Equation (2) without unacceptable material can be expressed as:

$$\begin{aligned}Z_1 = & \sum_{j=1}^{J} f_j S_{0j} + \sum_{j=1}^{J} v_j X_{0j} + \sum_{i=1}^{I}\sum_{j=1}^{J} E_j S_{ij} + \sum_{i=1}^{I}\sum_{j=1}^{J} m_j S_{ij} \\ & + \sum_{i=1}^{I}\sum_{j=1}^{J} c_{ij} X_{ij}\big(1 + (\alpha_j + \beta_j) S_{ij}\big) + \sum_{i=0}^{I}\sum_{j=1}^{J} X_{ij} b_j \big(1 + k_{ij}\big).\end{aligned} \tag{11}$$

- Minimisation of unacceptable material: this term can be stated as:

$$Z_2 = \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij} b_j.$$

- Minimisation of lateness: this term can be formulated as:

$$Z_3 = \sum_{i=1}^{I} \sum_{j=1}^{J} X_{ij} L_{ij}.$$

Constraints:

$$\Pr\left[\sum_{i=1}^{I} X_{ij} \geq D_j\right] \geq \alpha \tag{12}$$

$$G_{ij} S_{ij} \leq X_{ij} \leq H_{ij} \tag{13}$$

$$\Pr\left[\sum_{i=0}^{I} X_{ij} \geq w_j D_j\right] \geq \alpha \tag{14}$$

$$L_{ij} S_{ij} \leq L_i \tag{15}$$

$$X_j \geq X_{ij} \tag{16}$$

$$S_{i+1j} - S_{ij} \leq 0 \tag{17}$$

$$S_{ij} + S_{i+1j} \leq 1 \tag{18}$$

$$X_{ij} \geq 0 \tag{19}$$

$$0 \leq \alpha_j \leq 1 \quad \text{and} \quad 0 \leq \beta_j \leq 1. \tag{20}$$

Data is rarely finite and it must be used in a practical form. As such, some notable differences from the original model were designed as a probabilistic pattern. Equation (12) in a probability form is required to replace Equation (3) by using satisfaction level for meeting demand requirements. Similarly, Equation (14) is required to replace Equation (5). All other equations in the previous section are identical.

3.2 *The fuzzy multiple goal model*

The MOLP model can be transformed into a fuzzy multiple goal model since cost effectiveness is highly related to outsourcing options. The imprecise cost of unacceptable quality, lateness and effectiveness can in fact be formulated as a fuzzy multiple goal model through piecewise linear and continuous functions.

Equation (21) is a common fuzzy multiple goal model in which X is a decision vector of n dimension, $[Z_1(X), Z_2(X), \ldots, Z_L(X)]$ is the objective function, and $H(X) = 0$ and $G(X) \leq 0$ are equality and non-equality equations, respectively, as in actual situations:

$$\begin{aligned} &\min Z(X) = \min[Z_1(X), Z_2(X), \ldots, Z_L(X)]; \\ &\text{subject to :} \\ &\quad H(X) = 0 \\ &\quad G(X) \leq 0. \end{aligned} \tag{21}$$

The studied problem can be defined as a fuzzy multiple goal programming problem if the objective function is fuzziness. A max-min method is introduced to solve the fuzzy multiple goal problem. First, a membership function of $\mu[Z_1(X)]$ is assigned to each goal, and λ is defined as the maximum satisfaction as follows:

$$\lambda = \max_{x \in \Omega} \min\left\{\mu[Z_1(X)], \mu[Z_2(X)], \ldots, \mu[Z_L(X)]\right\} \tag{22}$$

The original model in the previous section may then be reformulated as follows:

$$\begin{aligned} &\max\ \lambda \\ &\lambda \leq \mu[Z_l(X)], \quad l = 1, 2, \ldots, L \\ &H(X) = 0 \\ &G(X) \leq 0. \end{aligned} \tag{23}$$

If the importance of each objective function differs, a weight is required, and Equation (23) can be written as:

$$\begin{aligned} &\max\ \mu[Z(X)] = \max\left\{w_1\mu[Z_1(X)] + w_2\mu[Z_2(X)] + \cdots + w_L\mu[Z_L(X)]\right\} \\ &H(X) = 0 \\ &G(X) \leq 0. \end{aligned} \tag{24}$$

or:

$$\begin{aligned} &\max \sum_{l=1}^{L} w_l \lambda_l \\ &\lambda_l \leq \mu[Z_l(x)], \quad l = 1, 2, \ldots, L \\ &0 \leq \lambda_1 \leq 1, \quad l = 1, 2, \ldots, L \\ &H(X) = 0 \\ &G(X) \leq 0, \end{aligned} \tag{25}$$

where, w_l is the weight for goals $0 \leq w_l \leq 1$ and $\sum_{l=1}^{L} w_l = 1$, and $\mu[Z_l(X)]$ is the membership function for $Z_l(X)$. To solve the unknown membership function of $\mu[Z_l(X)]$, the following method of Yang *et al.* (1991) is applied:

$$\mu\left[Z_l\left(X_{ij}\right)\right] = \begin{cases} \left[\frac{Z_l\left(X_{ij}\right) - Z_l^{\min}}{\tilde{Z}_l - Z_l^{\min}}\right], & Z_l^{\min} \leq Z_l\left(X_{ij}\right) \leq \tilde{Z}_l \\ \left[\frac{Z_l^{\max} - Z_l\left(X_{ij}\right)}{Z_l^{\max} - \tilde{Z}_l}\right], & \tilde{Z}_l \leq Z_l\left(X_{ij}\right) \leq Z_l^{\max} \\ 0, & \text{otherwise} \end{cases}. \tag{26}$$

In Equation (26), $\tilde{Z}_l$ is the mean value of the first fuzzy goal, and $Z_l^{\min}$ and $Z_l^{\max}$ are the values of lower and upper deviation limits of $\tilde{Z}_l$, respectively.

The membership function for each goal is determined as follows:

(1) Solve the optimal solution for each goal as an estimated value of $\tilde{Z}_l$.
(2) Determine $Z_l^{\max}$ and $Z_l^{\min}$ according to $\tilde{Z}_l$, $\tilde{Z} = (Z_l^{\max} + Z_l^{\min}) \div 2$.
(3) Substitute $\tilde{Z}_l$, $Z_l^{\max}$, and $Z_l^{\min}$ into Equation (26).

Equation (25) can be transformed as follows:

$$\max \sum_{l=1}^{L} w_l \lambda_l \tag{27}$$

$$\lambda \leq \mu[Z_l(X)] \tag{28}$$

$$\Pr\left[\sum_{i=1}^{I} X_{ij} \geq D_j\right] \geq \alpha \tag{29}$$

$$S_{ij} G_{ij} \leq X_{ij} \leq H_{ij} \tag{30}$$

$$\Pr\left[\sum_{i=0}^{I} K_{ij} X_{ij} \geq w_j D_j\right] \geq \alpha \tag{31}$$

$$S_j \geq S_{ij} \tag{32}$$

$$S_a - S_b \leq 0 \tag{33}$$

$$S_c + S_d \leq 1 \tag{34}$$

$$X_{ij} \geq 0 \tag{35}$$

$$0 \leq \alpha_j \leq 1 \quad \text{and} \quad 0 \leq w_j \leq 1 \tag{36}$$

$$\sum_{l=1}^{L} w_i = 1. \tag{37}$$

4. Implementation

The applicability of the proposed model can be demonstrated in an example of a power supply manufacture in Taiwan. The manufacturer accepts one of four potential vendors for its production orders. As suggested by the production manager, four power supply outsourcing vendors are proposed as feasible alternatives with four items. The manufacturer must select the most suitable vendor with item quantity in terms of cost effectiveness.

An expert panel is organised to support the production manager by providing relevant information. The panel involves managers in production, outsourcing, procurement, financial, and accounting departments. Related information includes information obtained directly from managers or from vendors' reports. Tables 1 to 7 show the detailed data for the firm, including costs, costs for make option, order material requirements, defect percentages, and lateness percentages. Costs related to quality and due date are essential considerations in the outsourcing decision. This case considers four outsourcing firms with four material items. Tables 3 to 7 show the basic data for purchasing cost, make cost, demand requirement, order limitation, quality, due date and others.

Table 1. Purchasing costs.

	Item				
Firm	1	2	3	4	Transaction cost
1	8	10	14	7.2	200
2	8.5	10.5	15	6.8	200
3	8.3	10.2	13.6	7.5	200
4	8.2	10.3	13.5	6.3	200

Table 2. Decision making costs.

	Item			
Cost	1	2	3	4
Fixed cost	7	9.5	11	7
Variable cost	100	200	300	200

Table 3. Demand data.

	Item			
Demand	1	2	3	4
Average demand	600	700	400	500
Standard deviation	20	50	10	40

Table 4. Order limitations.

	Capacity/order imitations			
Firm	Item 1	Item 2	Item 3	Item 4
1	200/25	400/25	200/25	600/25
2	300/25	300/25	500/25	300/25
3	400/25	300/25	200/25	300/25
4	500/25	200/25	200/25	200/25
Make capacity	350/0	500/0	100/0	200/0

Table 5. Quality requirements.

	Defect ratio (%)			
Firm	Item 1	Item 2	Item 3	Item 4
1	0.03	0.06	0.07	0.08
2	0.05	0.05	0.06	0.04
3	0.05	0.04	0.07	0.11
4	0.07	0.04	0.06	0.08
Capacity (make)	0.05	0.05	0.05	0.05

Table 6. Due date.

	Lateness (%)			
Firm	Item 1	Item 2	Item 3	Item 4
1	0.01	0.015	0.02	0.025
2	0.015	0.025	0.025	0.015
3	0.01	0.02	0.01	0.01
4	0.01	0.025	0.025	0.02
Make	0.015	0.025	0.01	0.01

Table 7. Relevant data for outsourcing items.

Others	Item 1	Item 2	Item 3	Item 4
Quality level	0.95	0.95	0.9	0.9
Technical discount	0.1	0.1	0.1	0.1
Material discount	0.2	0.2	0.2	0.2
Cost of techniques	80	100	100	150
Cost of material	1	1	0.5	0.5
Technical request	Yes	Yes	No	No
Material request	Yes	No	Yes	No

A cost perspective is associated with make and outsourcing production characteristics for varying fixed costs, variable costs, outsourcing costs, transition costs, quality costs and due date. A linear programming model with fuzzy multiple goals is formulated to construct vendor selection criteria. Criteria considered for product characteristics are costs, quality, due date, etc.

Data collection in early 2006 was followed by model formulation. The linear programming model with fuzzy multiple goals for optimising outsourcing effectiveness was completed and reported at the end of the same year.

4.1 *Result*

To test the applicability of the model under varying situations, the implementation was performed in three phases. Primary results describe the initial implementation of optimal

Table 8. Optimal order allocation: cost minimisation.

	Item				
Firm	1	2	3	4	Subtotal
1	200	400	0	26	626
2	0	0	0	300	300
3	226	300	198	0	724
4	200	65	200	200	665
Make decision	0	0	15	25	40
Order quantity	626	765	413	551	2355

Note: minimum cost: $21,336.06; minimum defects: 127.80 units, number of minimum lateness: 36.40 units.

Table 9. Optimal order allocation: defect minimisation.

	Unit				
Firm	Item 1	Item 2	Item 3	Item 4	Total
1	200	0	0	128	328
2	272	258	244	300	1074
3	149	300	0	0	449
4	0	200	151	99	450
Make	4	5	18	25	52
Total	625	763	413	552	2353

Note: minimum cost: $22,209; minimum defects: 116.43 units, number of minimum lateness: 45.21 units.

solutions given the stated goals of costs, quality and due date. The upper and lower limits of membership functions were then estimated. A weight for fuzzy outsourcing for order allocation was then performed. Finally, weight variations for the model were analysed.

4.2 *The initial results*

According to the main criteria described above, three objectives in terms of minimising costs, minimising defects, and minimising late deliveries were formulated, given the practical constraints requirements for satisfying individual items, capacity of outsourcing, product quality, due date, selection of outsourcing firms, etc. Tables 8 to 10 show the optimal solutions for costs, quality and due date, and the following novel findings are observed:

(1) As indicated, cost can be reduced to $21,366.06 without violating quality or due date restrictions. Similarly, assuming no other restrictions apply unacceptable quality can be minimised to 116.43 units in Table 9 compared to 127.80 units in Table 8 and 141.67 units in Table 10. However, order allocation for outsourcing firms and material items in each solution varies.

(2) One implication of the solution is the required trade-off between goals. For instance, the optimal solution for cost goal of $21,336.06 in Table 8 increased to

Table 10. Optimal order allocation: due date.

	Item				
Firm	1	2	3	4	Total
1	200	400	200	0	800
2	0	0	0	239	239
3	226	300	200	300	1026
4	200	65	0	0	265
Make	0	0	14	13	27
Total	626	765	414	552	2357

Note: minimum cost: \$21,713.73; minimum defects: 141.67 units, number of minimum lateness: 32.77 units.

Table 11. Solutions for cost, quality, and due date.

	Middle	Upper	Lower
Cost	21,336	23,336	19,336
Quality	116.43	146.43	86.43
Due date	32.77	42.77	22.77

\$22,209 in Table 9 and \$21,713.73 in Table 10 corresponding to both the goals of quality and due date.

To derive a more adaptable and flexible solution, the optimal compromise between three goals must be identified.

4.3 *Solution for the membership function*

The fuzzy multiple goals are defined by a triangular membership function as represented in Equation (26). The degree of satisfaction with the three fuzzy multiple goals minimising costs, defects and late deliveries were obtained by $\tilde{Z}_1 = 21{,}336$ in Table 8, $\tilde{Z}_2 = 116.23$ in Table 9, and $\tilde{Z}_3 = 32.77$ in Table 10. These values indicate the best possible solution since no other goals were considered when obtaining their values. The maximum and minimum limits for the deviation of each fuzzy multiple goal were the same on both sides: 2000, 30 and 10 for minimising costs, defects and late deliveries, respectively. Regarding the goal basis, Table 11 and Figure 1 show that upper deviations limits were $Z_1^{\max} = 23{,}336$, $Z_2^{\max} = 146.43$, and $Z_3^{\max} = 42.77$ relevant to $Z_1^{\min} = 19{,}336$, and lower deviation limits were $Z_2^{\min} = 86.43$ and $Z_3^{\min} = 22.77$. Table 12 shows the solutions for the membership function.

4.4 *Results for weighted fuzzy model*

To enhance the flexibility of the model, weights were introduced. A weight was assigned to each criterion according to the importance of the relevant goal. Goals of cost, quality and due date were used as objective function values to analyse the interaction and satisfactory achievement of specific goals. To delineate the change of weights of specific goals, initial

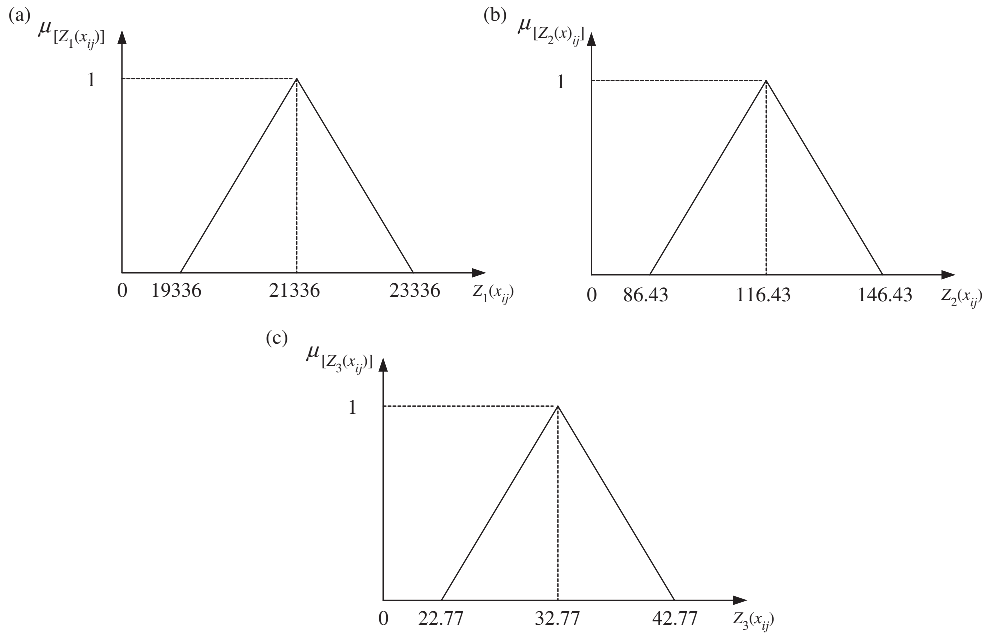

Figure 1. Membership function of different goals; (a) $Z_1(x_{ij})$, (b) Z_2 (x_{ij}), and $Z_3(x_{ij})$.

Table 12. Values of membership functions.

$\mu[Z_1(X_{ij})]$	Solution between lower and mid limit	$\left[\frac{Z_1(x_{ij}) - 19{,}336}{21{,}336 - 19{,}336}\right]$	$19{,}336 \le Z_1(x_{ij}) \le 21{,}336$
	Solution between mid and upper limit	$\left[\frac{23{,}336 - Z_1(x_{ij})}{23{,}336 - 21{,}336}\right]$	$21{,}336 \le Z_1(x_{ij}) \le 23{,}336$
	Others	0	
$\mu[Z_2(X_{ij})]$	Solution between mid and lower limit	$\left[\frac{Z_2(x_{ij}) - 86.43}{116.43 - 86.43}\right]$	$86.43 \le Z_2(x_{ij}) \le 116.43$
	Solution between mid and upper limit	$\left[\frac{146.43 - Z_2(x_{ij})}{146.43 - 116.43}\right]$	$116.43 \le Z_2(x_{ij}) \le 146.43$
	Others	0	
$\mu[Z_3(X_{ij})]$	Solution between lower and mid limit	$\left[\frac{Z_3(x_{ij}) - 22.77}{32.77 - 22.77}\right]$	$22.77 \le Z_3(x_{ij}) \le 32.77$
	Solution between mid and upper limit	$\left[\frac{42.77 - Z_3(x_{ij})}{42.77 - 32.77}\right]$	$32.77 \le Z_3(x_{ij}) \le 42.77$
	Others	0	

weight ratios (w_i) of 0.8, 0.1, and 0.1 for cost (w_1), quality (w_2) and due date (w_3) goals, respectively, were set followed by a series of changes. Twelve cases were organised. Each test case was a specific combination of (w_1, w_2, w_3), where $w_1 \in \{0.1, 0.2, 0.3, 0.4, 0.6, 0.8\}$, $w_2 \in \{0.1, 0.2, 0.3, 0.4, 0.6, 0.8\}$, and $w_3 \in \{0.1, 0.2, 0.3, 0.4, 0.6, 0.8\}$. Table 15 depicts the solution for the initial weight with the OBJ values of \$21,348.49 for cost goal,

Table 13. Order allocation.

	Item				
Firm	1	2	3	4	Total
1	200	295	46	0	541
2	87	174	0	298	559
3	177	175	200	43	595
4	161	120	153	187	621
Make	0	0	15	24	39
Order quantity	625	764	414	552	2355

Note: $w_1 = 0.8$, $w_2 = 0.1$, and $w_3 = 0.1$.

Table 14. Results for satisfaction measure.

	Cost	Quantity	Due date
Weights (w_i)	0.8	0.1	0.1
OBJ	21,348.49	124.34	36.36
Satisfaction (λ)	0.94	0.74	0.64

Note: overall satisfaction degree $(\lambda) = 0.892694$.

124.34 units for quality goal and 36.36 units for due date goal. Tables 13 to 15 show the relevant results, and significant findings are stated below:

(1) Compared to the original OBJ values of $21,336, 116.43 units, and 32.77 units, the initial weight was clearly set too high. However, a satisfactory equilibrium could be achieved while balancing multiple goals.
(2) Due to the high weight setting, the value of cost goal consistently and satisfactorily approximated the optimal solution for a single objective.
(3) The satisfactory achievement of goals was consistent with weight ratio. A goal with high weight ratio indicated high satisfaction. For instance, satisfaction with due date reached as high as one in the case of $w_1 = 0.1$, $w_2 = 0.1$, and $w_3 = 0.8$.
(4) For overall satisfaction, the satisfactory cost goal was consistently high, which indicated that the cost of order changing procedure did not significantly differ between make and outsourcing firms. However, effects on the goal of due date were significant.
(5) Order change affected satisfaction, and the highest satisfaction was achieved in the case of a high level of due date weight ratio with a low level of cost weight ratio.
(6) In the transition from fuzzy multiple goal model to single goal model, the membership function was one satisfactory constraint. As such, the membership function setting may have affected the satisfaction scale.

5. Conclusions

Outsourcing is an increasingly important means of enhancing manufacturing flexibility and practical models are needed. In production systems design, integrating manufacturing decisions with outsourcing is now an important strategy for expanding manufacturing

Table 15. Test of weight ratios.

Case	Weights (w_1, w_2, w_3)		Cost goal	Quality goal	Due date goal	Satisfactory scale
1	(0.8, 0.1, 0.1)	OBJ	21,348.49	124.34	36.36	0.89
		λ	0.94	0.74	0.64	
2	(0.6, 0.2, 0.2)	OBJ	21,348.49	124.34	36.36	0.87
		λ	0.99	0.74	0.64	
3	(0.4, 0.3, 0.3)	OBJ	21,456.80	125.18	35.97	0.79
		λ	0.94	0.71	0.68	
4	(0.2, 0.4, 0.4)	OBJ	21,538.21	127.12	35.02	0.75
		λ	0.90	0.64	0.77	
5	(0.1, 0.1, 0.8)	OBJ	21,715.56	137.13	32.77	0.91
		λ	0.81	0.31	1	
6	(0.2, 0.2, 0.6)	OBJ	21,680.61	133.60	33.00	0.84
		λ	0.83	0.43	0.98	
7	(0.3, 0.3, 0.4)	OBJ	21,437.23	127.19	35.00	0.79
		λ	0.95	0.64	0.78	
8	(0.4, 0.4, 0.2)	OBJ	21,387.10	121.09	37.84	0.83
		λ	0.974451	0.84	0.49	
9	(0.1, 0.8, 0.1)	OBJ	21,672.83	116.89	42.77	0.87
		λ	0.83	0.98	0.00	
10	(0.2, 0.6, 0.2)	OBJ	21,487.1	121.09	37.84	0.79
		λ	0.92	0.84	0.49	
11	(0.3, 0.4, 0.3)	OBJ	21,353.87	123.82	36.49	0.79
		λ	0.99	0.75	0.63	
12	(0.4, 0.2, 0.4)	OBJ	21,437.23	127.19	35.00	0.82
		λ	0.95	0.64	0.78	

scope and capacity. However, the current method of outsourcing analysis is not sufficiently responsive for decision making. A model for analysing investments is needed because of the widely varying physical settings and competitive advantages of global production systems. Without a systematic approach for analysing critical components, the advantages of outsourcing are difficult to predict.

This work developed a fuzzy multiple goal model with a *cost-effectiveness* perspective for optimising outsourcing decisions. Relevant outsourcing components are quality, technological transition and material preparation. The vagueness and imprecision of costs incurred due to unacceptable quality, lateness, and effectiveness are formulated in the fuzzy multiple goal model through piecewise linear functions.

A power supply manufacturer in Taiwan was used to illustrate the applicability of the proposed model. The implementation of the model in the illustrative case above demonstrated its applicability. In the practical case, the proposed model realistically predicted outsourcing decision procedure. The implementation results demonstrate that the outsourcing logic can help explain the varying decision making parameters.

Further studies examining various aspects of the outsourcing supply chain as well as varying model formulation are required. For example, additional service criteria such as logistics limitations of outsourcing decision making are also required. Future research could further investigate issues relevant to the proposed model and expand its application in different situations.

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