F O U N D A T I O N S O F C O M P U T I N G A N D D E C I S I O N S C I E N C E S
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Fuzzy Multi-Objective Optimization to Evaluate the Performance of Suppliers Taking Into Account the Visibility and Supply Chain Risk

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Abstract. Adequate and desirable connections between suppliers and customers necessitate an appropriate flow of information. Therefore, a promising and proper data collaboration in the supply chain is of tremendous significance. Thus, the study's main objective is to provide multiple objective programming models under uncertain conditions to assess the performance of suppliers. To meet that aim, a case study for the reliability assessment of the presented model is carried out. That section is associated with supply chain visibility (SCV). Likewise, the likelihood of unpredicted and undesirable incidents involving supply chain risk (SCR) is taken into consideration. The intimate relation between visibility and risk of the supply chain is deemed efficient for the performance of the supply chain. Incoherence in maximization and minimization of SCR and SCV and other factors,

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including costs, capacity, or demand, necessitates multiple objective programming models to assess suppliers' performance to accomplish the before-mentioned aims. The study's results indicate the high reliability of the proposed model. Besides, the numeral results reveal that decision-makers in selecting suppliers mainly decrease SCR and then attempt to enhance SCV. In conclusion, the provided model in the study can be a desirable model for analyzing and estimating supplier performance with SCR and SCV simultaneously.

Keywords: supply chain visibility; suppliers performance; supply chain risk; information flow, programming models.

1. Introduction

Supply Chain Management plays an indispensable role in globalized business competition by facilitating the integrated management of information, raw materials, and products between suppliers, manufacturers, distributors, retailers, and customers. Supply Chain Management also enhances production flexibility, transport speed, information access, and complexity management capabilities of businesses. Considering these features, all business executives and academic researchers acknowledge how much Supply Chain Management can contribute to building a competitive strategy and improving business productivity and profitability. One of Supply Chain Management 's most important challenges is choosing and interacting with suppliers. Information is one of the main resources that businesses use to overcome such challenges [1]. A good relationship between suppliers and their clients contributes to reliable information flows, enhancing efficiency [2]. Therefore, it is important to make sure accurate information about demand, transportation costs, and other logistics issues are shared across the supply chain in a timely manner.

In supply chains that only have a single supplier, there is always a risk that production will be halted or slowed down by unexpected events, causing unintended delays in shipments and leading to interruption in the production schedules of downstream components of the supply chain [3].

Zsidisin [4] defines this type of risk as the likelihood of an incident related to inbound supply from individual supplier failures or the supply market taking place, resulting in the buying firm's incapability to gratify customer needs or pose threats to customer safety and life. Even the events that affect one member or process of a supply chain tend to have direct or indirect implications for other members in a variety of ways. Supply chain disruptions are indeed a substantial problem for several businesses. A detailed description of supply risk and how it can be assessed is provided in [4]. Researchers have used the value-at-risk approach to estimate the supply risk [4]. The main factor in improving product design based on standardization is to reduce the risk of production and support systems [5,6]. Factors that affect managers' perceptions of supply risks have been studied and the sources or causes of supply risk have been categorized [7]. Researchers have provided a review of previous studies on the potential factors or sources of supply risks [8-10]. A review of the literature in this field reveals that the main issue of interest in SCR management is risk visibility, as ensuring good risk visibility makes supply chain planning much more effective and greatly benefits the operational efficiency of the supply chain [10, 11]. Thus, this study is more focused on this aspect of SCR.

In [12], researchers observed good risk visibility in less than half of the supply chains they investigated. Therefore, considering the recent chain disruptions in Asia and the reports provided in the subject literature, one may question how we can choose suppliers so that supply risks and supply chain disruptions are minimized and how we can maximize supply risk visibility without going over budget.

Recent studies on SCV have attracted a great deal of attention from Supply Chain Management researchers and experts [13]. About 79% of companies surveyed from around the world have stated that poor SCV is one of their main concerns [14]. Furthermore, 90% of the surveyed supply chains have acknowledged that their current supply chain technology fails to provide timely information for cash flow and budget planning of their finance departments, which is alarming. It is argued that the technologies like RFID can be utilized to enhance SCV by facilitating information sharing and flow, which will finally boost supply chain performance [15,16]. Furthermore, it has been shown that the implementation of SCV improvement practices can increase supply chain stability and reduce the bullwhip effect [17]. For example, this can be done by creating a system of point-of-sale (POS) information sharing throughout the supply chain. SCV is determined as supply chain players' likelihood to access or supply the needed timely data from/to related supply chain partners for more desirable decision support [18-20]. In [10], it is stated that global logistics operators seem to benefit more from global supply chain visibility. Therefore, we still need a better understanding of the common issues that exist in the field of SCV and SCR.

Multi-objective integer programming (MOIP) is mainly regarded as a virtual research arena as numerous practical situations need discrete representations by integer variables, and multiple decision-makers have to manage several goals. Several notable practical conditions where the MOIP problems discover their utilizations are supply chain design, scheduling, financial planning, and also logistics planning [18,20]. The MOIP issues are practically tricky and complicated, as the majority of them, even their single-objective versions, fall into the category of computationally intractable problems [15,21].

Considering the literature review and also the fact that in today’s competitive market, estimating the performance of suppliers in a supply chain is strategically necessitated to satisfy three groups of objectives in terms of cost, risk, and risk visibility in downstream members, this current study intended to propose and devise multiple objective programming models under uncertain conditions to evaluate and predict the performance of suppliers. This study attempts to scrutinize the relationship between SCV and SCR in supplier selection, considering the possibility of unpredicted and undesirable incidents involving SCR. The study’s outcomes demonstrate the provided model could be an efficient model to examine and estimate supplier performance with SCR and SCV at the same time. Hence, the results of the study this study can make a notable contribution to enhancing the suppliers’ performance.

2. Methodology

The proposed mathematical model was formulated with the goal of integrating SCV and SCR for better supplier selection. The proposed model, which is called the multi-objective integer programming model, has 3 purposes: maximizing visibility, minimizing risk, and minimizing cost. The structure of this model is presented below (Table 1).

Table 1. The structure of the presented model

Indexes	
Suppliers' index	i
Index of raw materials (parts)	j
Variables od decision	
Quantity of part i supplied by supplier j	Q_{ij}
A binary variable that is defined by if part i is supplied by supplier i	Y_{ij}
= 1 if part i is supplied by supplier j = 0 otherwise	Y_{ij}
Factors	
Accessible budget for SCV improvement for part i	B_i
Supplier j's production capacity	C_i
Supply risk reduction cost for part i provided by supplier j	CR_{ij}
Expense of improving SCV up to the existing level for part i supplied by supplier j	CV_{ij}
Need for part i	D_i
Minimum order size for part i supplied by supplier j	m_{ij}
Price of part i supplied by supplier j	P_{ij}
Monetary effect resulting from the supply risk of part i supplied by supplier j	lR_{ij}
Supply risk for part i supplied by supplier j	R_{ij}
Maximum allowable supply risk for part i	R_i
Risk visibility of supply chain whether part i is supplied by supplier j	V_{ij}
Minimum required risk visibility for part i	V_i

2.1. Model: Visibility maximization

$$\text{Max visibility} = \sum_i \sum_j V_{ij}\, Y_{ij} \tag{1}$$

Risk minimization:

$$\text{Min risk} = \sum_i \sum_j R_{ij}\, Y_{ij} \tag{2}$$

Cost minimization:

$$\text{Min cost} = \sum_i \sum_j V_{ij}\, CV_{ij} Y_{ij} + \sum_i \sum_j R_{ij}\, CR_{ij} Y_{ij} + \sum_i \sum_j l\, R_{ij}\, Y_{ij} + \sum_i \sum_j P_{ij}\, Q_{ij} \tag{3}$$

$$\sum_i \sum_j V_{ij}\, C\, V_{ij} Y_{ij} \le B_i \qquad \forall i \tag{4}$$

$$\sum_i V_{ij}\, Y_{ij} \ge V_i \qquad \forall i \tag{5}$$

$$\sum_i Q_{ij} = D_i \qquad \forall i \qquad (6)$$

$$\sum_j Q_{ij} \leq C_j Y_{ij} \qquad \forall j \qquad (7)$$

$$\sum_i R_{ij} Y_{ij} \leq R_i \qquad \forall i \qquad (8)$$

$$Q_{ij} \geq m_{ij} Y_{ij} \qquad \forall\, i,j \qquad (9)$$

$$Q_{ij} \leq N Y_{ij} \qquad \forall i \qquad (10)$$

$$Q_{ij} \geq 0 \qquad \forall\, i,j \qquad (11)$$

$$Y_{ij} \in \{1,0\} \qquad \forall\, i,j \qquad (12)$$

Eq. (4) limits SCV to a scheduled fund for all suppliers. Eq. (5) sets the minimum amount of visibility for each part. Eq. set (6) sets the size (quantity) of demand for each part or raw material. Eq. set (7) acts as a capacity constraint for suppliers. Eq. set (8) limits the maximum allowable risk in getting each part from suppliers. Eq. (9) sets the minimum size of orders for each part for all suppliers. Eq. set (10) helps avoid conflict between decision variables (N is a large number). The Eq. set (11) ensures that the parameters only take non-negative values, and eventually, Eq. set (12) leads the decision variables to only take integer values.

Given the fuzzy nature of data commonly used in supplier selection problems, the original model was transformed into a Fuzzy Multi-Objective Programming (FMOP) model. This FMOP model is a new formulation of the crisp (fuzzy) supplier selection model introduced in [18].

2.2. Solution algorithm for the modified FMOP model

The algorithm for solving the modified FMOP model comprises the following steps:

(1) Build the model on the basis of existent information regarding SCR and SCV and determine capacity and demand constraints for several suppliers and parts.

(2) Address the issue as a single-objective one for all of the objective functions. Regarding each of the objective functions, detect the lower and upper bound solutions utilizing the Max-Min technique [19]. Given the fact that SCR and SCV are modeled as fuzzy triangular numbers (U, M, L), the lower and upper bound solutions are able to be acquired from the next crisp models.

For maximizing the objective functions, the equations(13-24) are applied utilizing the Max-Min technique [17-20]:

$$U_1 = \text{Max} \sum_i \sum_j (V_{ij})^U Y_{ij} \quad (13)$$

$$U_2 = \text{Max} \sum_i \sum_j (R_{ij})^U Y_{ij} \quad (14)$$

$$U_3 = \text{Max} \sum_i \sum_j (V_{ij})^U CV_{ij} Y_{ij} + \sum_i \sum_j (R_{ij})^U CR_{ij} Y_{ij} + \sum_i \sum_j IR_{ij} Y_{ij} + \sum_i \sum_j P_{ij} Q_{ij} \quad (15)$$

$$\sum_j (V_{ij})^L CV_{ij} Y_{ij} \leq R_i \qquad \forall \text{ i} \quad (16)$$

$$\sum_j (V_{ij})^U Y_{ij} \leq V_i \qquad \forall \text{ i} \quad (17)$$

$$\sum_j (R_{ij})^L Y_{ij} \leq R_i \qquad \forall \text{ i} \quad (18)$$

For the minimization of objective functions:

$$L_1 = \text{Min} \sum_i \sum_j (V_{ij})^L Y_{ij} \quad (19)$$

$$L_1 = \text{Min} \sum_i \sum_j (R_{ij})^L Y_{ij} \quad (20)$$

$$L_3 = \text{Min} \sum_i \sum_j (V_{ij})^L CV_{ij} Y_{ij} + \sum_i \sum_j (R_{ij})^L CR_{ij} Y_{ij} + \sum_i \sum_j IR_{ij} Y_{ij} + \sum_i \sum_j P_{ij} Q_{ij} \quad (21)$$

$$\sum_i (V_{ij})^U CV_{ij} Y_{ij} \leq B_i \qquad \forall \text{ i} \quad (22)$$

$$\sum_i (V_{ij})^L Y_{ij} \geq V_i \qquad \forall \text{ i} \quad (23)$$

$$\sum_j (R_{ij})^U Y_{ij} \leq R_i \qquad \forall \text{ i} \quad (24)$$

(3) Discover the corresponding membership functions for all of the objective functions.

The membership functions $\mu_i x(i)$ for the maximization and minimization fuzzy objective functions are given by respectively Equations (25) and (26), where L_1, L_2, and L_3 are the lower bounds and U_1, U_2, and U_3 are the upper bounds for the three functions:

$$\mu_j\left(Z_j(x)\right)=\begin{cases}1 & if\ Z_j(x)\geq U_j\\ \dfrac{Z_j(x)-L_j}{U_1-L_1} & if\ L_j\leq Z_j(x)\leq U_j\\ 0 & if\ Z_j(x)\leq L_j\end{cases} \quad \forall \text{ i} \qquad (25)$$

$$\mu_j\left(Z_j(x)\right)=\begin{cases}1 & if\ Z_j(x)\geq U_j\\ \dfrac{U_j-Z_j(x)}{U_j-L_j} & if\ L_j\leq Z_j(x)\leq U_j\\ 0 & if\ Z_j(x)\geq U_j\end{cases} \quad \forall \text{ i} \qquad (26)$$

(4) Defuzzify the fuzzy constraints by weighted averaging employing a beta probability distribution function.

(5) Reformulate the problem and solve the FMOP model as a crisp single-objective model utilizing the outcomes of Steps 2 to 4.

Here, FMOP is solved with the crisp single-objective weighting model proposed in [20-27] for problems with K objectives. In the following equations (27-33), λ_K denotes the level of achievement of the k-th objective:

$$\lambda_k\leq\mu_k\left(Z_k(x)\right)\qquad k=1,2,\dots,k \qquad (27)$$

$$\sum_i\left[\left(\frac{1}{6}\right)V_{ij}^{p}CV_{ij}Y_{ij}+\left(\frac{4}{6}\right)V_{ij}^{m}CV_{ij}Y_{ij}+\left(\frac{1}{6}\right)V_{ij}^{o}CV_{ij}Y_{ij}\right]\leq B_i \quad \forall \text{ i} \qquad (28)$$

$$\sum_i\left[\left(\frac{1}{6}\right)V_{ij}^{p}Y_{ij}+\left(\frac{4}{6}\right)V_{ij}^{m}Y_{ij}+\left(\frac{1}{6}\right)V_{ij}^{o}Y_{ij}\right]\leq V_i \quad \forall \text{ i} \qquad (29)$$

$$\sum_i\left[\left(\frac{1}{6}\right)R_{ij}^{p}Y_{ij}+\left(\frac{4}{6}\right)R_{ij}^{m}Y_{ij}+\left(\frac{1}{6}\right)R_{ij}^{o}Y_{ij}\right]\leq R_i \quad \forall \text{ i} \qquad (30)$$

$$\lambda_k\in[0,1]\qquad k=1,2,\dots,K \qquad (31)$$

$$\sum_{k=1}^{k}w_k=1,\qquad w_k\geq 0 \qquad (32)$$

$$Y_{ij}\in[0,1] \quad \forall \text{ i} \qquad (33)$$

2.3. Results and discussion

According to [21], in many situations, case study strategies are used to develop models with the help of relevant personal, group, social, or organizational information. Thus, they are similar to experimental studies and can be validated by similar methods.

In the case of this study, the buyer intends to purchase three types of raw materials called GFR1, GFR2, and GFR3 from one or multiple suppliers such that several objectives in terms of risk minimization, visibility maximization, and cost minimization are satisfied. The monthly amounts of GFR1, GFR2, and GFR3 required to meet the demand for the end product (different types of composite pipes) during the planning period are 60,000, 45,000, and 35,000Kg, respectively. These materials can be obtained from 3 suppliers with different production capacities and different prices. The prices offered by the suppliers are given in

Table (2). The monthly production capacity of suppliers 1, 2, and 3 is 70,000, 80,000, and 90,000Kg respectively. Each supplier has also set a minimum order size, which is 5000, 6000, and 7000kg for suppliers 1, 2, and 3, respectively.

Table 2. Prices of raw materials ($/Kg)

Supplier 3	Supplier 2	Supplier 1	Material
27	28	30	GRF1
37	39	41	GRF2
49	51	53	GRF3

To improve its SCV, the company (Dena Sanat) has set aside different amounts of budget for these three suppliers. This has been done on the basis of geographical location and certain information processing capabilities. The budget allocated to Suppliers 1, 2, and 3 are $100,000, $120,000, and $130,000, in turn.

For the sale of simplicity, we use triangular fuzzy numbers to model SCR and SCV. Suppose $\widetilde{m} = (l, m, r)$ is a triangular fuzzy number with the membership function $\mu_{\widetilde{m}}(x)$ formulated below:

$$\mu_{\widetilde{m}} = \begin{cases} \frac{x-1}{m-1}, & (1 \le x \le m) \\ \frac{r-x}{r-m}, & (m \le x \le r) \end{cases} \tag{34}$$

In [22], researchers have defined SCR as the expected impact of events on the buyer. Following their approach, one can formulate a probabilistic model for SCR with 3 various probability levels (high, low, and medium). For each of the probability levels, the effect can be modeled as its financial equivalent. For this purpose, the impact of each supplier can be estimated based on the potential risk of events and the resulting financial losses. The risk profile of suppliers considered in this study is given in Table (3).

Table 3. Risk profile of the considered suppliers

Risk damage	Risk probability	Supplier
$1,000,000	0.4	1
$400,000	0.3	2
$250,000	0.3	3

How suppliers are selected may cause different amounts of supply risk depending on their capacity, capability, geographical proximity, and natural environment [23]. For instance, supplier 1, with a risk probability of 0.4, has $1,000,000 risk damage. In contrast, supplier 3, with a risk probability of 0.3, suffers just a quarter of that amount.

Risk levels may also change from one material to the other, as these materials are used in different composite products, which are sold in different markets at different prices. In Table 4, the potential risks involved in buying materials from different suppliers are expressed as fuzzy triangular numbers.

Table 4. Fuzzy risk of purchase from each supplier

Supplier 3	Supplier 2	Supplier 1	Material
(2.4,3,3.5)	(1.2,2,2.5)	(0.5,1,1.3)	GRF1
(2.1, 2.8, 3.4)	(1.5, 2.1, 2.6)	(0.3, 0.8, 1.2)	GRF2
(2.4, 3.1, 3.7)	(1.7, 2.2, 2.7)	(0.4, 1.1, 1.6)	GRF3

Risk visibility of the relationship between the company and its suppliers can be improved by implementing RFID-based and other such information systems. It is assumed that the more the company invests in the RFID system, the more desirable the visibility will be. Considering the fact the 3 suppliers come from various areas and have different processing capacities, the cost required to boost the visibility from its current level (CV_{ij}) will be \$20,000 for Supplier 1, \$22,000 for Supplier 2, and \$25,000 for Supplier 3. Risk visibility for buying each material from each supplier is modeled in three levels: low, medium, and high. The fuzzy triangular numbers assigned to these visibility levels are given in Table (5). Developing a minimum visibility level for each raw material is required to make the purchasing process more efficient. This minimum must be decided based on the importance of the material for the supply chain. This decision is made based on the importance of the material for the manufacturing of the final product to ensure that the more important materials will continue to flow into and across the supply chain without disruption. Here, we set the minimum threshold values to 1.5 for GRF1, 2 for GRF2, and 2.5 for GRF3.

Table 5. Fuzzy risk visibility of the materials purchased from the suppliers

Supplier 3	Supplier 2	Supplier 1	Material
(0.6, 1.1, 1.7)	(1.6, 2.3, 2.8)	(2.4, 3.2, 3.8)	GRF1
(0.7, 1.3, 1.8)	(1.4, 2.0, 2.5)	(2.3, 2.9, 3.4)	GRF2
(0.5, 1.1, 1.7)	(1.3, 1.9, 2.4)	(2.4, 3.3, 3.9)	GRF3

The results obtained by building the FMOP model on the basis of the information above and then formulating the problem as a single-objective model with the Max-Min method for each of the objective functions. The fuzzy membership functions obtained for each objective are given in Table (6).

Table 6. Membership function for each objective

Objective Functions	$\mu = 0$	$\mu = 1$	$\mu = 0$
Z1	-	35.9	6.6
Z2	21.3	7.6	-
Z3	7.519	400.6	101.000

Next, the fuzzy constraints were defuzzified with the aid of a beta probability distribution [20-23]. In probability statistics and theory, the beta distribution is a family of continuous probability distributions specified on the interval [0, 1] parameterized by 2

positive shape parameters, characterized by beta and alpha, that emerge as exponents of the random variable control the shape of the distribution. The most probable state's weight was set to 4/6, and the weights of pessimistic and optimistic states were set to 1/6. The outcome of this process was the values of SCV and SCR as crisp numbers. We then reformulated the problem and solved the modified FMOP model as a single-objective model with crisp values applying the outcomes acquired in the previous steps. In this process, it was assumed that decision preferences for the three objective functions have the same weights (i.e. 0.33 for every objective function).

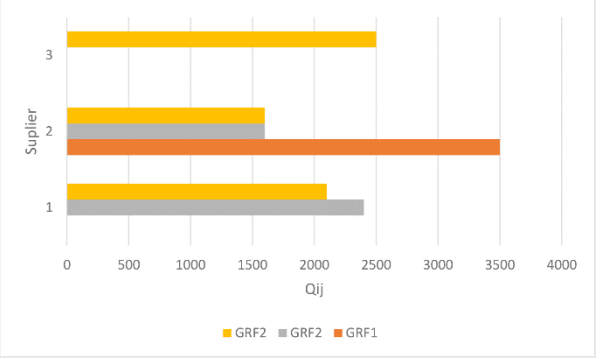


Figure 1. Comparison of the size of orders placed with the three suppliers

As shown in Figure 1, while GRF1 is supplied from only two suppliers, GRF3 is supplied from all three suppliers. As can be seen, Supplier 2 is used to supply all three materials, which is because it outperforms other suppliers in terms of quality and prices. This procedure can be used as an efficient means of assigning orders to suppliers.

The results show that the cost minimization objective (λ_3) is fulfilled more than the other two objectives. This matches the decision-making preferences of most companies. Also, the risk minimization objective (λ_2) is fulfilled more than the visibility maximization objective. This may be because most decision-makers are risk-averse and therefore prefer reducing SCR instead of improving SCV.

GRF3 has the least allowable risk among the three materials because the products made from it are sold at higher prices. Therefore, Supplier 1 is selected to supply GRF2 because it has high visibility and low risk. While Supplier 3 sells the product at a lower price, it is riskier, and its failure will have a greater impact. Therefore, this supplier is selected to supply GRF3. Supplier 2 offers products at moderate prices, but it has a moderate level of SCV and is exposed to a moderate level of SCR. This supplier is selected to supply two raw materials. Therefore, setting an appropriate SCR strategy and the efforts to improve SCV have benefited Supplier 2.

3. Conclusion

Overall, over the course of this study, it was attempted to provide multiple objective programming models under uncertain conditions to evaluate the performance of suppliers.

To that end, a case study for the reliability assessment of the presented model is performed. The results of the study indicate that the proposed FMOP method provides a good model of supplier performance with SCR and SCV considered simultaneously. Considering the results, this model can elevate the suppliers' performance.

The results suggest that companies are much more interested in reducing their supply risks than improving their SCV. Nonetheless, suppliers that can offer reduced SCR, improved SCV, or a balanced combination of both will be able to gain more market share. Also, to achieve full supply chain visibility, companies need to make massive investments in this area. Consequently, this study can contribute to boosting the suppliers' performance.

Regarding future studies, they can determine the weights of criteria utilizing various fuzzy analytic hierarchy process methods, including Logarithmic fuzzy preference programming (LFPP) or Fuzzy logarithmic Least Square method (FLLSM).

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