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Research Article

A Grey-Fuzzy Multiobjective Model for Supplier Selection and Production-Distribution Planning Considering Consumer Safety

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Most of the recent product recall incidents indicate that effective management of suppliers and production-distribution planning may play a vital role in increasing product safety. This study explores the opportunities to increase the product safety by analyzing the performance of suppliers and production-distribution system. More precisely, this research analyzes the impact of suppliers' performance on overall profit of supply chain and impact of increasing consumer safety on total profit of supply chain. The novelty of this study is the development of integrated supplier selection and production-distribution model considering consumer risk and product safety. The proposed model is a grey multiobjective model which considers imprecise information as grey parameters. Furthermore, a novel grey-weighted ε-constrained (GWECON) method is developed to solve the proposed multiobjective model.

1. Introduction

Recent product recall incidents triggered increased interests of consumers on product safety and quality [1]. Supply chain quality management is an important practice tool to achieve food safety [2]. Food safety or product safety refers to the reduction in the probability that a product used by the consumer will result in illness, injury, or death [3]. The "consumer risk" is a potential risk of reaching an unsafe product to the consumer market and causes harmful effect [4]. Product safety is a fact of life in today's growing world economy. Consumers need to be assured that the products they buy will fulfil standards of quality and safety when consumed as well as when manufactured. It shows that the industry has to deal with their product safety issues and create a trust for the consumers. Safety can be contributed by all members of the supply chain. Each can play their roles by ensuring that the unsafe and below standard products must not go into the market. In the supply chain at every stage including manufacture, design, raw material, storage, testing, marketing, and packaging, there are many opportunities to make products safer. In this paper, chain dispersion methodology is used to optimize the traceability of product in distribution channel which results in minimization of consumer risk by effective identification or elimination of underrated products. Furthermore, the literature evidenced that most product recalls incurred are due to contaminated raw materials or underrated semifinished and finished products. This reveals that selection of an underrated supplier is one of the key factors which leads to a product recall.

This study evaluates a suppliers' performance and production-distribution system from product safety perspective. The literature presented so far shows that product safety is becoming one of the primary focuses of supply chain management. In real-world supplier selection and production-distribution problem, the decision makers attempt to (1) select suitable set of suppliers such that overall performance of suppliers meets the product safety criteria, (2) allocate the optimal purchasing quantities to selected suppliers, (3) set production levels for each product to meet the uncertain demands of customers, and (4) make right decisions regarding distribution of products to customers such that overall risk to consumers should be minimum. To attain these aims, an integrated multiobjective supplier selection and production-distribution planning model is proposed. The aim of this model is to minimize total consumer risks and maximize total suppliers' performance attributes and total profit of supply chain. A grey systems theory-based approach is proposed to deal with uncertainties associated with proposed mathematical models. The advantage of the proposed method is that it requires neither any probability distribution nor fuzzy membership function. To solve the multiobjective grey mathematical model, a novel grey-fuzzy solution methodology is developed called a grey-weighted ε-constrained method (GWECON). The developed solution methodology is an extension of the ε-constrained method. The original ε-constrained method is not efficient with more than two objective functions [5]. Furthermore, this method assumes equal importance to all the constrained objective functions. The proposed GWECON method minimizes these limitations of the ε-constrained method.

2. Literature Review

The term "product safety" is described as policies designed to protect the people from risks associated with product they purchased and use every day. Furthermore, product safety refers to the reduction in the probability that product used by consumer will result in illness, injury, or death [3]. Product safety problems in a supply chain can arise at any stage of supply chain process and will transfer from one stage to others [6]. Hence, it will be very difficult to effectively identify the source of problem in supply chain. According to Whipple et al. [7], food supply chains involve a lot of susceptibilities in terms of safety perspective. Firstly food chains consist of perishable natural products which if not timely and safely managed can be noxious to consumers [8]. Secondly, these are globally interconnected and long chains, resulting in higher exposure to risk [7]. According to Voss et al. [9], safety is the least important criteria in scrutiny of suppliers compared to delivery and price; this least important criterion is one of the major reasons for increased food safety incidents.

Traceability has become the essential business function to consistently supply products with required safety and quality assurance to achieve consumer confidence [10]. It is difficult to manage product quality in a multitier supply chain which has low traceability for the origin of materials [11]. Not only is effective traceability a valuable tool to manage food quality and safety risks, but it also promotes the development of effective food supply chain management [1, 12]. However, the efforts on building traceability systems have often been separated from profitable supply chain management strategies. This hinders not only the enthusiasm of investment in efficient traceability systems but also the potential to improve supply chain efficiency through the integration of traceability with operations management functions [13]. Manufacturers are not getting satisfactory results despite the availability of different traceability systems to minimize the number of recalls. These manufacturers always try to trace the raw material batches contaminated by microbial contamination in the food industry and defected component batches in assembly lines, but they failed because of a nonoptimized traceability system. Moe [14] classified traceability concepts into internal traceability and chain traceability. Chain traceability refers to track the products from purchasing, production, storage, and distribution to customers, whereas internal traceability refers to track the batches internally into one stage of the supply chain. Traceability optimization concept in the supply chain is relatively new and very few works have been done in this area. Wang, Li, and O'brien [13] used batch dispersion methodology to optimize the batch size considering traceability factor. Memon et al. [15] used the same methodology to analyze traceability optimization and shareholders profit under the recall crisis. Rong and Grunow [16] applied the chain traceability concept to optimize the chain dispersion in food distribution system. In this study, chain traceability is referred to as chain dispersion and is defined as a function of the number of customers served by a batch. Figure 1 demonstrates the chain dispersion concept.

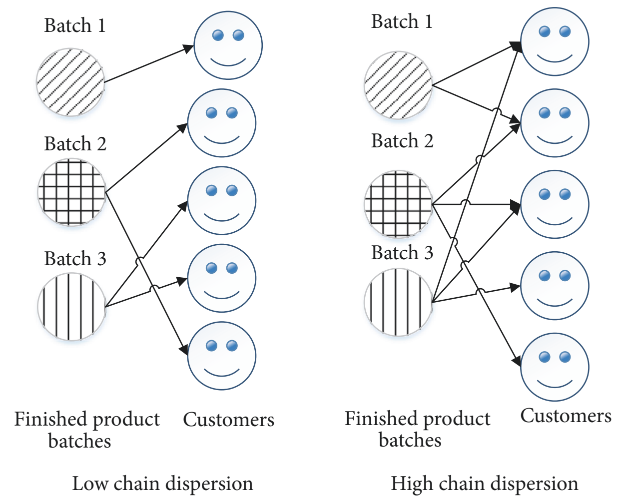

Figure 1: Chain dispersion concept.

From the above discussion, two aspects are considered as important with reference to this study. The first important point of discussion is about the integration of procurement, production, and distribution planning problem. Integration of procurement, production, and distribution planning is the main focus of supply chain management to control the efficient flow of material among suppliers, manufactures, and customers. That is the reason a major thrust of recent literature is about the development of optimization models that integrate purchasing, production, and distribution planning in the supply chain [17]. However, most of the recent literature focuses on cost and delivery optimization. To the best of the author's knowledge, the study presented in this research is primary work which focuses on product safety/consumer safety perspective in supply chain planning decision. The

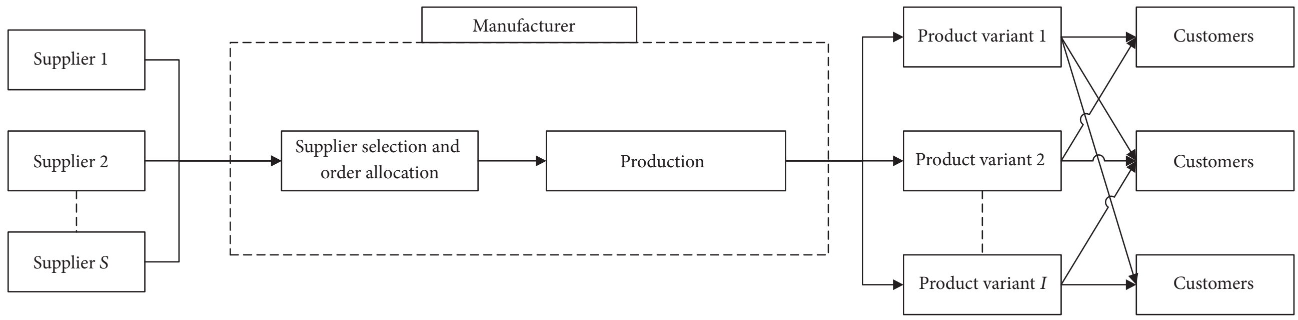

Figure 2: Supply chain network under consideration.

second important point of discussion is about the solution methodology which is required to solve the considered planning problem. This study developed a novel approach to solve multiobjective optimization problem using joint grey systems theory and fuzzy theory. Inclusion of grey mathematical programming in proposed model and fuzzy based solution methodology increases the usefulness of proposed study.

3. Problem Description

A manufacturer wants to satisfy the various demands of customers by producing multiple product variants such as different colour, flavour, and other options. Product variants may or may not share common raw materials and semifinished products. These raw materials and semifinished products are procured from selected suppliers based on multiple criteria. Since each supplier has limited capacity to produce the required raw material and semifinished products. Therefore, it is important to determine optimal quantity allocation to each selected supplier. Figure 2 shows the supply chain network under consideration.

3.1. Model Formulation. A mixed integer linear programming (MILP) model is proposed for the integrated supplier selection and production-distribution planning. The manufacturer wants to produce I product variants demanded by J customers using raw material and semifinished products provided by S suppliers in a multiperiod planning horizon. These suppliers differ with respect to price, capacity, and product safety risks. The model considered as a multiobjective problem that should give the following answers to decision makers:

(i) Which candidate supplier should be selected based on multiple selection criteria to minimize product safety risks?

(ii) How much quantity of raw material/semifinished products should be purchased from selected supplier(s)?

(iii) What are the optimal production and distribution quantities of the products to maximize profit with minimum consumer risk?

(iv) How to manage inventory levels of raw materials and finished products?

In order to design the structure of understudy supply chain problem, certain assumptions must be made for setting the boundary of the model. The following assumptions are made for the formulation of the proposed mathematical model.

(i) It is a multiproduct and multiperiod problem.

(ii) All the relevant information is available as grey parameters.

(iii) Production capacities are estimated based on setups and machine capacities.

(iv) Inventory of materials may be kept for use in future periods.

(v) A pool of predetermined suppliers is available.

(vi) Performance rating of different suppliers can be estimated subjectively.

(vii) Each supplier can only supply certain types of materials.

Notations and Parameters

Notations

b: batch ID

i: product variant index, $i = 1, 2, \ldots, I$

o: OR material index, $o = 1, 2, \ldots, O$

m: Option index in each OR material, $m = 1, 2, \ldots, M$

l: AND material index, $l = 1, 2, \ldots, L$

s: supplier index, $s = 1, 2, \ldots, S$

j: customer index, $j = 1, 2, \ldots, J$

t: time period index, $t = 1, 2, \ldots, T$

Parameters

$\otimes D_{ijt}$: demand for product variant i by customer j in period t

$\otimes C_i$: unit production cost for product variant i

$\otimes \not{C}_i$: setup cost of product variant i

$\otimes \varpi_{somt}$: selling price offered by supplier s for OR material option m in period t

$\otimes \omega_{slt}$: selling price offered by supplier s for AND material l in period t

$\otimes H_{om}^{OR}$: inventory holding cost for OR material option m

$\otimes H_{l}^{AND}$: inventory holding cost for AND material l

$\otimes H_{i}$: inventory holding cost of product variant i

Pr_{omi}^{OR}: quantity of OR material option m required to produce unit product variant i

Pr_{li}^{AND}: quantity of AND material l required to produce unit product variant i

$\otimes P_{it}$: selling price of product variant i in period t

$\otimes R_{oms}^{OR}$: performance rating for OR material with option m purchased from supplier s

$\otimes R_{ls}^{AND}$: performance rating for AND material purchased from supplier s

$\otimes Cp_{lst}^{AND}$: capacity of AND material at supplier s in period t

$\otimes Cp_{omst}^{OR}$: capacity of OR material option m at supplier s in period t

$\otimes AQ_{oms}^{OR}$: Minimum acceptable order quantity of OR material option m by supplier s

$\otimes AQ_{ls}^{AND}$: minimum acceptable order quantity of AND material l by supplier s

$\otimes Cp^{pr}$: batch production capacity

$\otimes pr_{i}$: probability of recall for product variant i

$$u_{li}^{AND} = \begin{cases} 1, & \text{if AND material } l \text{ is used in variant } i \\ 0, & \text{otherwise} \end{cases}$$
$$u_{omi}^{OR} = \begin{cases} 1, & \text{if OR material option } m \text{ is used in variant } i \\ 0, & \text{otherwise} \end{cases}$$
$$\mu_{ls}^{AND} = \begin{cases} 1, & \text{if AND material } l \text{ can be provided by supplier } s \\ 0, & \text{otherwise} \end{cases}$$
$$\mu_{oms}^{OR} = \begin{cases} 1, & \text{if OR material option } m \text{ can be provided by supplier } s \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

Decision Variables

$$\pi_{ibt} = \begin{cases} 1, & \text{if product variant } i \text{ with batch ID } b \text{ is produced in period } t \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

Q_{ibt}: quantity of product variant i with batch ID b produced in period t

$$y_{ibjt} = \begin{cases} 1, & \text{if product variant } i \text{ with batch ID } b \text{ serves customer } j \text{ in period } t \\ 0, & \text{otherwise} \end{cases}$$
$$\begin{matrix} \theta_{\{e,f\in j,e\neq f\}}^{\quad ibeft} \\ \theta'^{\quad ibeft}_{\{e,f\in j,e\neq f\}} \end{matrix} \begin{cases} = 1, & \text{if product variant } i \text{ with batch ID } b \text{ serves customer } e \text{ and } f \text{ in period } t \\ = 0, & \text{otherwise} \end{cases} \tag{3}$$

A_{bijt}: quantity of product variant i with batch ID b sold to customer j in period t

Q^{OR}_{somt}: quantity of OR material option m purchased from supplier s in period t

$$x_{somt} = \begin{cases} 1, & \text{if OR material option } m \text{ is purchased form supplier } s \text{ in period } t \\ 0, & \text{otherwise} \end{cases} \quad (4)$$

Q^{AND}_{slt}: quantity of AND material l purchased from supplier s in period t

$$x'_{slt} = \begin{cases} 1, & \text{if AND material } l \text{ is purchased form supplier } s \text{ in period } t \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

I^{OR}_{omt}: inventory level of OR material with option m in period t

I^{AND}_{lt}: inventory level of AND material l in period t

I_{ibt}: inventory level of product variant i with batch ID b in period t

Objective Functions

Z_1 = maximize total profit

Z_2 = maximize suppliers performance attributes

Z_3 = minimize consumer risk

3.2. Model Objectives and Constraints Estimations

3.2.1. Total Profit Estimation. The first objective function of the proposed model is total profit. It includes the difference between the total revenue generated by selling all the product variants demanded by customers and total cost as shown in (10). Total cost includes purchasing cost of OR and AND materials, production cost (variable and setup cost), and inventory holding cost of OR, AND materials, and finished product variants.

Equation (6) estimates the total revenue generated by selling product variants to customers in all planning periods.

$$\text{Total revenue (TR)} = \sum_t \sum_i \sum_b \sum_j \otimes P_{it} A_{ibjt} \quad (6)$$

Equation (7) calculates the total purchasing cost of OR and AND materials from all selected suppliers in all planning periods.

$$\text{Total purchasing cost (TPC)} = \sum_t \sum_s \sum_o \sum_m \otimes \varpi_{somt} Q^{OR}_{somt} + \sum_t \sum_s \sum_l \otimes \omega_{slt} Q^{AND}_{slt} \quad (7)$$

Equation (8) estimates the total production cost which is the sum of the unit production cost and setup cost.

$$\text{Total production cost (TPRC)} = \sum_t \sum_i \sum_b \otimes C_i Q_{ibt} + \sum_t \sum_i \sum_b \otimes \cancel{C}_i \pi_{ibt} \quad (8)$$

Total inventory holding cost is estimated in (9). It consists of raw materials holding cost (OR material and AND material) and finished product holding cost.

$$\begin{aligned} \text{Total inventory holding cost (TIHC)} &= \sum_t \sum_o \sum_m \otimes H^{OR}_{om} I^{OR}_{omt} + \sum_t \sum_l \otimes H^{AND}_l I^{AND}_{lt} \\ &+ \sum_t \sum_i \sum_b \otimes H_i I_{ibt} \end{aligned} \quad (9)$$

$$\text{Total Profit} = \text{TR} - (\text{TPC} + \text{TPRC} + \text{TIHC}) \quad (10)$$

3.2.2. Supplier Performance Attributes Estimation. The second objective function of the proposed model is the supplier performance attribute. It estimates the total supplier performance rating based on product safety criteria. In this model, the performance rating of suppliers is multiplied by the proportion of material quantity purchased from a selected supplier. Hence, purchasing a larger quantity of material from lower rating supplier will result in reduced total supplier performance rating and vice versa. Readers may refer to Memon et al. [18] for further study on supplier selection and order allocation using grey systems theory. Equation (11) estimates the total supplier performance attribute for both OR and AND materials.

Total supplier performance attribute is

$$\frac{\sum_t \sum_o \sum_m \sum_s \otimes R^{OR}_{oms} Q^{OR}_{somt}}{Pr^{OR}_{omi} \sum_i \sum_j \otimes D_{ijt}} + \frac{\sum_t \sum_l \sum_s \otimes R^{AND}_{ls} Q^{AND}_{slt}}{Pr^{AND}_{li} \sum_i \sum_j \otimes D_{ijt}} \quad (11)$$

3.2.3. Consumer Risk Estimation. When assessing risks, the severity of the hazard, the likelihood that consumer will be exposed to the hazards and likelihood that exposure will result in an adverse health effect have all to be considered [19]. Therefore, the following two factors are considered in order to estimate the consumer risk:

(1) Severity of the hazard

(2) Likelihood of the hazard.

In this study, the *severity* indicates the nature and exposure level of the hazard. This means that expected number of consumers affected by the product recall. This can be estimated by the dispersion level of each finished product batch. It shows that an increase in finished product batch size and dispersion level will result in increased consumer risk. The *likelihood* refers to the probability of recall based on the known history of performance and complaints of similar product types. In practice, managers have difficulty in evaluating the likelihood of hazards due to uncertainty and lack of knowledge. As an alternative, risk assessors rank likelihood qualitatively in terms of linguistic variables such as rare, occasional, and frequent. In this study grey linguistic numbers are used to capture the vagueness in the linguistic subjectivity of risk definitions. Considering the above definitions, the total consumer risk can be estimated as in (12). The objective function minimizes the chain dispersion by controlling the binary variable θ.

$$\text{Total consumer risk} = \sum_i \sum_b \sum_{e\in j} \sum_{\substack{f\in j\\ e\neq f}} \sum_t \otimes\, pr_i \theta_{bieft} \tag{12}$$

Constraints. Constraints (13) and (14) ensure that purchase quantities of OR material and AND material should satisfy minimum acceptable order quantity criteria by suppliers.

$$\sum_o \sum_m Q^{OR}_{somt} \geq \otimes AQ^{OR}_{oms} \quad \forall s, o, m, t \tag{13}$$

$$\sum_l Q^{AND}_{slt} \geq \otimes AQ^{AND}_{ls} \quad \forall s, l, t \tag{14}$$

Constraints (15) and (16) are the supplier's capacity constraints. The purchase quantities of OR and AND material from each supplier should be less than their capacities. Additionally, it also forces to control the supplier's ability to produce certain materials. The capacity of the supplier is one of the important criteria for supplier evaluation for both economic and product safety point of views. If more suppliers are included for same material/product type then it creates traceability problems. Wang, Li, and O'brien [13] and Wang et al. [20] explained traceability optimization problem related to a number of raw material batches and their sizes.

$$Q^{OR}_{somt} \leq \otimes Cp^{OR}_{omst} \mu^{OR}_{oms} x_{somt} \quad \forall s, o, m, t \tag{15}$$

$$Q^{AND}_{slt} \leq \otimes Cp^{AND}_{slt} \mu^{AND}_{ls} x'_{slt} \quad \forall s, l, t \tag{16}$$

The total amount of OR material with option m and AND material l required to produce a unit finished product is given in (17) and (18), respectively. Materials are available either from previous periods or from the procurement in the current period.

$$I^{OR}_{om(t-1)} + \sum_s Q^{OR}_{somt} \geq \sum_i \sum_b u^{OR}_{omi} Q_{ibt} Pr^{OR}_{omi} \quad \forall s, o, m, i, t \tag{17}$$

$$I^{AND}_{l(t-1)} + \sum_s Q^{AND}_{slt} \geq \sum_i \sum_b u^{AND}_{li} Q_{ibt} Pr^{AND}_{li} \quad \forall s, l, i, t \tag{18}$$

Constraints (19) and (20) balance the inventory level of OR materials option m and AND material l.

$$I^{OR}_{omt} = I^{OR}_{om(t-1)} + \sum_s Q^{OR}_{somt} - \sum_i \sum_b u^{OR}_{omi} Q_{ibt} Pr^{OR}_{omi} \qquad \forall s, o, m, i, t \tag{19}$$

$$I^{AND}_{lt} = I^{AND}_{l(t-1)} + \sum_s Q^{AND}_{slt} - \sum_i \sum_b u^{AND}_{li} Q_{ibt} Pr^{AND}_{li} \qquad \forall s, l, i, t \tag{20}$$

Similarly, constraint (21) ensures the balance of inventory levels of product variant i. Constraints (22) and (23) impose the initial and ending inventory conditions to balance the inventory.

$$I_{ibt} = I_{ib(t-1)} + Q_{ibt} - \sum_j A_{bnijt} \quad \forall i, b, t \tag{21}$$

$$\begin{aligned} I^{AND}_{l(t=0)} &= 0, \\ I^{AND}_{l(t=T)} &= 0, \\ I^{OR}_{om(t=0)} &= 0, \\ I^{OR}_{om(t=T)} &= 0, \\ &\forall o, m, l \end{aligned} \tag{22}$$

$$\begin{aligned} I_{i(t=0)} &= 0, \\ I_{i(t=T)} &= 0 \\ &\forall i \end{aligned} \tag{23}$$

Constraints (24) check whether the specific batch is produced in time t.

$$\begin{aligned} Q_{ibt} &\leq \otimes Cp^{pr} \pi_{bit}, \\ \pi_{bit} &\leq Q_{ibt} \\ &\forall i, b, t \end{aligned} \tag{24}$$

Constraint (25) makes sure that customer demands are fulfilled in each period. Constraints (26) check whether the specific batch is delivered to the customer, where M is a very large number.

$$\sum_i \sum_b A_{bnijt} = \otimes D_{nijt}, \quad \forall t, j \tag{25}$$

$$\begin{aligned} A_{ibjt} &\leq M y_{ibjt}, \\ y_{ibjt} &\leq A_{ibjt} \\ &\forall t, j \end{aligned} \tag{26}$$

Constraints (27) force to control the binary variables related to chain dispersion. It forces to $\theta_{ibeft} = 1$ and $\theta'_{ibeft} = 0$, if batch b is served to two different customers e and f simultaneously and vice versa.

$$\begin{aligned} & 2\theta_{ibeft} + \theta'_{ibeft} = y_{ibet} + y_{ibft}, \\ & \theta_{ibeft} + \theta'_{ibeft} \leq 1 \\ & \forall (e, f) \in j, e \neq f, b, t \end{aligned} \tag{27}$$

Constraints (28)-(29) define the domain of decision variables.

$$\begin{aligned} & A_{bijt}, Q_{ibt}, Q^{OR}_{somt}, Q^{AND}_{slt}, I^{OR}_{omt}, I^{AND}_{lt}, I_{ibt} \\ & \geq 0 \text{ and Integer}, \quad \forall s, o, m, l, i, t \end{aligned} \tag{28}$$

$$\begin{aligned} & \pi_{nit}, x_{somt}, x'_{slt}, y_{ibjt}, \theta_{ibeft}, \theta'_{ibeft} \in \{0, 1\} \\ & \forall s, o, m, l, i, t \end{aligned} \tag{29}$$

4. Grey-Fuzzy Solution Methodology

The proposed model is the grey multiobjective model that considered imprecise information as grey parameters. To solve this problem, a two-phase solution methodology is proposed. In the 1st phase, the grey multiobjective model presented above is converted into a crisp model called a white model. In this stage pay-off values of objectives are estimated by solving each objective separately. Multiobjective optimization problem encompasses recognitive uncertainty due to the subjective judgment of DMs. Therefore, grey model objectives are addressed in the solution methodology in a fuzzy mathematical framework by assigning membership functions. Then in the 2nd phase, a grey-weighted ε-constraint (GWECON) method is proposed by improving the original formation of a ε-constraint method for solving the multiobjective problem. The solution methodology steps are summarized as follows.

Step 1. Convert proposed grey multiobjective mathematical model into its equivalent crisp form

The proposed grey mathematical model can be converted into its equivalent crisp form using whitenization weight (α) as shown below. The value of α is between 0 and 1, having no weightage to 100% weightage. Please refer to Liu and Forrest [21] for whitenization of grey numbers.

$$\begin{aligned} & \text{Total Profit (TP)} \\ & = \sum_t \sum_i \sum_b \sum_j \left(\alpha \underline{P}_{it} + (1-\alpha) \overline{P}_{it}\right) A_{ibjt} \\ & - \left(\sum_t \sum_s \sum_o \sum_m \left(\alpha \underline{\omega}_{somt} + (1-\alpha) \overline{\omega}_{somt}\right) Q^{OR}_{somt} \right. \\ & + \sum_t \sum_s \sum_l \left(\alpha \underline{\omega}_{slt} + (1-\alpha) \overline{\omega}_{slt}\right) Q^{AND}_{slt} \\ & + \sum_t \sum_i \sum_b \left(\alpha \underline{C}_i + (1-\alpha) \overline{C}_i\right) Q_{ibt} \\ & + \sum_t \sum_i \sum_b \left(\alpha \underline{\cancel{C}}_i + (1-\alpha) \overline{\cancel{C}}_i\right) \pi_{ibt} \\ & + \sum_t \sum_o \sum_m \left(\alpha \underline{H}^{OR}_{om} + (1-\alpha) \overline{H}^{OR}_{om}\right) I^{OR}_{omt} \\ & + \sum_t \sum_l \left(\alpha \underline{H}^{AND}_l + (1-\alpha) \overline{H}^{AND}_l\right) I^{AND}_{lt} \\ & \left. + \sum_t \sum_i \sum_b \left(\alpha \underline{H}_i + (1-\alpha) \overline{H}_i\right) I_{ibt} \right) \end{aligned} \tag{30}$$

$$\begin{aligned} & \text{Total supplier performance attribute (TSPA)} \\ & = \frac{\sum_t \sum_o \sum_m \sum_s \left(\alpha \underline{R}^{OR}_{oms} + (1-\alpha) \overline{R}^{OR}_{oms}\right) Q^{OR}_{somt}}{Pr^{OR}_{omi} \sum_i \sum_j \left(\alpha \underline{D}_{ijt} + (1-\alpha) \overline{D}_{ijt}\right)} \\ & + \frac{\sum_t \sum_l \sum_s \left(\alpha \underline{R}^{AND}_{ls} + (1-\alpha) \overline{R}^{AND}_{ls}\right) Q^{AND}_{slt}}{Pr^{AND}_{li} \sum_i \sum_j \left(\alpha \underline{D}_{ijt} + (1-\alpha) \overline{D}_{ijt}\right)} \end{aligned} \tag{31}$$

$$\begin{aligned} & \text{Total consumer risk (TCR)} \\ & = \sum_i \sum_b \sum_{e \in j} \sum_{\substack{f \in j \\ e \neq f}} \sum_t \left(\alpha \underline{pr}_i + (1-\alpha) \overline{pr}_i\right) \theta_{bieft} \end{aligned} \tag{32}$$

Constraints

$$\sum_o \sum_m Q^{OR}_{somt} \geq \left(\alpha \underline{AQ}^{OR}_{oms} + (1-\alpha) \overline{AQ}^{OR}_{oms}\right) \quad \forall s, o, m, t \tag{33}$$

$$\sum_l Q^{AND}_{slt} \geq \left(\alpha \underline{AQ}^{AND}_{ls} + (1-\alpha) \overline{AQ}^{AND}_{ls}\right) \quad \forall s, l, t \tag{34}$$

$$\begin{aligned} & Q^{OR}_{somt} \leq \left(\alpha \underline{Cp}^{OR}_{omst} + (1-\alpha) \overline{Cp}^{OR}_{omst}\right) \mu^{OR}_{oms} x_{somt} \\ & \forall s, o, m, t \end{aligned} \tag{35}$$

$$\begin{aligned} & Q^{AND}_{slt} \leq \left(\alpha \underline{Cp}^{AND}_{slt} + (1-\alpha) \overline{Cp}^{AND}_{slt}\right) \mu^{AND}_{ls} x'_{slt} \\ & \forall s, l, t \end{aligned} \tag{36}$$

$$I_{om(t-1)}^{OR} + \sum_{s} Q_{somt}^{OR} \geq \sum_{i}\sum_{b} u_{omi}^{OR} Q_{ibt} Pr_{omi}^{OR} \quad \forall s, o, m, i, t \tag{37}$$

$$I_{l(t-1)}^{AND} + \sum_{s} Q_{slt}^{AND} \geq \sum_{i}\sum_{b} u_{li}^{AND} Q_{ibt} Pr_{li}^{AND} \quad \forall s, l, i, t \tag{38}$$

$$I_{omt}^{OR} = I_{om(t-1)}^{OR} + \sum_{s} Q_{somt}^{OR} - \sum_{i}\sum_{b} u_{omi}^{OR} Q_{ibt} Pr_{omi}^{OR} \quad \forall s, o, m, i, t \tag{39}$$

$$I_{lt}^{AND} = I_{l(t-1)}^{AND} + \sum_{s} Q_{slt}^{AND} - \sum_{i}\sum_{b} u_{li}^{AND} Q_{ibt} Pr_{li}^{AND} \quad \forall s, l, i, t \tag{40}$$

$$I_{ibt} = I_{ib(t-1)} + Q_{ibt} - \sum_{j} A_{bnijt} \quad \forall i, b, t \tag{41}$$

$$\begin{gathered} I_{l(t=0)}^{AND} = 0, \\ I_{l(t=T)}^{AND} = 0, \\ I_{om(t=0)}^{OR} = 0, \\ I_{om(t=T)}^{OR} = 0, \\ \forall o, m, l \end{gathered} \tag{42}$$

$$\begin{gathered} I_{i(t=0)} = 0, \\ I_{i(t=T)} = 0 \\ \forall i \end{gathered} \tag{43}$$

$$\begin{gathered} Q_{ibt} \leq \left(\alpha \underline{Cp}^{pr} + (1-\alpha)\overline{Cp}^{pr}\right) Cp^{pr} \pi_{bit}, \\ \pi_{bit} \leq Q_{ibt} \\ \forall i, b, t \end{gathered} \tag{44}$$

$$\sum_{i}\sum_{b} A_{bnijt} = \left(\alpha \underline{D}_{nijt} + (1-\alpha)\overline{D}_{nijt}\right) \quad \forall t, j \tag{45}$$

$$\begin{gathered} A_{ibjt} \leq M y_{ibjt}, \\ y_{ibjt} \leq A_{ibjt} \\ \forall t, j \end{gathered} \tag{46}$$

$$\begin{gathered} 2\theta_{ibeft} + \theta'_{ibeft} = y_{ibet} + y_{ibft}, \\ \theta_{ibeft} + \theta'_{ibeft} \leq 1 \\ \forall (e, f) \in j,\ e \neq f, b, t \end{gathered} \tag{47}$$

$$\begin{gathered} A_{bijt}, Q_{ibt}, Q_{somt}^{OR}, Q_{slt}^{AND}, I_{omt}^{OR}, I_{lt}^{AND}, I_{ibt} \\ \geq 0 \text{ and Integer}, \quad \forall s, o, m, l, i, t \end{gathered} \tag{48}$$

$$\begin{gathered} \pi_{nit}, x_{somt}, x'_{slt}, y_{ibjt}, \theta_{ibeft}, \theta'_{ibeft} \in \{0, 1\} \\ \forall s, o, m, l, i, t \end{gathered} \tag{49}$$

Step 2. Obtain pay-off values of each objective function under the given constraints by solving equivalent crisp model. This will result in positive ideal solution (*PIS*) and negative ideal solution (*NIS*).

Step 3. Develop fuzzy membership function for each objective using pay-off values as follows:

$$\mu_{TP} = \begin{cases} 0, & \text{If } TP \leq TP^{NIS} \\ \dfrac{TP - TP^{NIS}}{TP^{PIS} - TP^{NIS}}, & \text{If } TP^{NIS} < TP < TP^{PIS} \\ 1, & \text{If } TP \geq TP^{PIS} \end{cases} \tag{50}$$

$$\mu_{TSPA} = \begin{cases} 0, & \text{If } TSPA \leq TSPA^{NIS} \\ \dfrac{TSPA - TSPA^{NIS}}{TSPA^{PIS} - TSPA^{NIS}}, & \text{If } TSPA^{NIS} < TSPA < TSPA^{PIS} \\ 1, & \text{If } TSPA \geq TSPA^{PIS} \end{cases} \tag{51}$$

$$\mu_{TCR} = \begin{cases} 1, & \text{If } TCR \leq TCR^{PIS} \\ \dfrac{TCR^{NIS} - TCR}{TCR^{NIS} - TCR^{PIS}}, & \text{If } TCR^{PIS} < TCR < TCR^{NIS} \\ 0, & \text{If } TCR \geq TCR^{NIS} \end{cases} \tag{52}$$

where μ_{TP}, μ_{TSPA}, and μ_{TCR} represent the satisfaction degree of total profit, total supplier performance attribute, and total consumer risk, respectively.

Step 4. Solve the multiobjective model using grey-weighted ε-constraint method (GWECON).

Assume the following multiobjective problem (MOP):

$$\begin{aligned} \max \quad & (\mu_1(x), \mu_2(x), \ldots, \mu_n(x)) \\ \text{s.t} \quad & x \in S \end{aligned} \tag{53}$$

where $\mu_1(x), \mu_2(x), \ldots, \mu_n(x)$ are the n objective functions, x is the vector of decision variables, and S is the feasible region. In the ε-constraint method one objective function with most important priority is optimized with other objective functions in constraints as shown below:

$$\begin{aligned} \max \quad & \mu_1(x) \\ \text{s.t} \quad & \mu_2(x) \geq \varepsilon_2, \\ & \mu_3(x) \geq \varepsilon_3, \\ & \ldots \\ & \mu_n(x) \geq \varepsilon_n \\ & x \in S \end{aligned} \tag{54}$$

The efficient solutions of the problem are obtained by parametrical variation of ε_n in constrained objective functions.

There are the following two main drawbacks in the above ε-constraint method formulation:

(1) The method is not efficient with more than two objective functions [5].

(2) The method assumes equal importance to all the constrained objective functions.

This study tries to address the above issues in proposed GWECON method. Using the proposed method, problem (53) can be transformed as follows:

$$\begin{aligned} \max \quad & \mu_1(x) + \{\tilde{\otimes}\beta_2\lambda_2 + \tilde{\otimes}\beta_3\lambda_3 + \ldots + \tilde{\otimes}\beta_n\lambda_n\} \\ \text{s.t} \quad & \mu_2(x) - \lambda_2 \geq \varepsilon_2, \\ & \mu_3(x) - \lambda_3 \geq \varepsilon_3, \\ & \ldots \\ & \mu_n(x) - \lambda_n \geq \varepsilon_n \\ & x \in S \end{aligned} \tag{55}$$

The slack/surplus variables (λ_n) are incorporated in constrained objective function and at the same time these variables are added in objective function with grey-weights ($\tilde{\otimes}\beta_n$) showing the importance of constrained objectives. The original ε-constraint method with more than two objective functions is not efficient enough to find a feasible solution at every iteration. The proposed GWECON method tackles the limitation of the ε-constraint method by generating feasible solution in every iteration of the solution algorithm by assigning slack or surplus variables. It is also important in multiobjective optimization to consider the importance of objectives. The ε-constraint method assumes equal importance for all constrained objectives which is not all true in real-world problems. The proposed GWECON method not only considered the importance of constrained objectives but also considered the subjectivity of DMs preferences by incorporating a grey linguistic based method for estimating objective weights.

Step 5. Specify the values of the minimum acceptable degree of satisfaction (ε_n) for GWECON method and relative importance of each objective function and then solve the model developed in Step 4. If DMs are not satisfied with the model solution, then provide another efficient solution by adjusting values of ε_n. Also, if DMs want to modify whitenization weight, then repeat process from Step 1.

5. Application of Proposed Model and Solution Methodology

A numerical example with three-level generic bill of material (GBOM) is presented as shown in Figure 3. Assume that the manufacturer offers a product family (PF) to meet customer requirements in three (j = 3) different customer zones for three planning periods (t = 3). Customers have the flexibility to choose burgers from available options like chicken or fish meat with cheese or egg topping, where L1 (bun) and L2 (vegetables) are AND material, O1 and O2 are OR materials, and PF11 and PF12 are intermediate products. The number on arrows represents the quantity of material required to produce unit of its parent item. The details about OR material options are given in Table 1. These materials can be procured from fourteen (s =14) available suppliers. The total number of product variants (PV) in product family can be estimated as $2 \times 2 = 4$.

Table 1: Material options available as per customer requirement.

Material attributes	Material options available to customers
O1 represents the meat	O11: Chicken
	O12: Fish
O2 represents the topping flavours	O21: Cheese topping
	O22: Egg topping

Table 2 shows the suppliers' performance rating with respect to product safety criteria. Table 3 shows the demand of product variants at various customer zones. Tables 4 and 5 show the price offered by the supplier for OR and AND materials, respectively. The GBOM of burger product is designed in such a way that it requires a unit of chicken or fish patties and an egg or slice of cheese. It is assumed in this case example that these required materials are available from suppliers in bulk units (that is, kilogram and dozens). Based on these assumptions, the capacities of suppliers are randomly selected between [162000, 181000] ~ [272000, 287000] units. Additionally, the capacities of suppliers are considered more than required quantities of materials in order to analyze single-sourcing and multisourcing decisions. Table 6 includes unit production cost and setup cost for each product variant. Batch production capacity is assumed as [40000, 42000] units. Table 7 shows the unit holding cost of purchased materials and finished product variants. Probability of recall is estimated in Table 8, assuming that three DMs take part in decision-making process. Lastly, Table 9 shows the estimated importance of model objectives.

5.1. Results and Discussion. The proposed grey model and steps of solution methodology are coded in Lingo optimization software. Following the steps of the proposed solution methodology, the pay-off values are estimated as shown in Table 10 at α = 0.5. The results clarify the tradeoff between considered model objectives. It can be seen from the results that maximizing the profit will result in higher consumer risk and lower supplier performance. This is due to the fact that manufacturers try to (i) minimize the raw material cost by procuring low-cost material which ultimately lowers the total supplier's performance attribute and (ii) minimize the production cost by reducing a total number of setups in each planning period which increases the consumer risk due to high chain dispersion. Similarly, optimizing other objectives will have a negative impact on total profit objective. Graphical representation of objective tradeoff is shown in Figure 4. Additionally, head-to-head comparisons are also performed between a profitable supply chain, consumer risk, and supplier performance attributes for a clear understanding of compromise solutions. Please refer to Figures 5 and 6 for

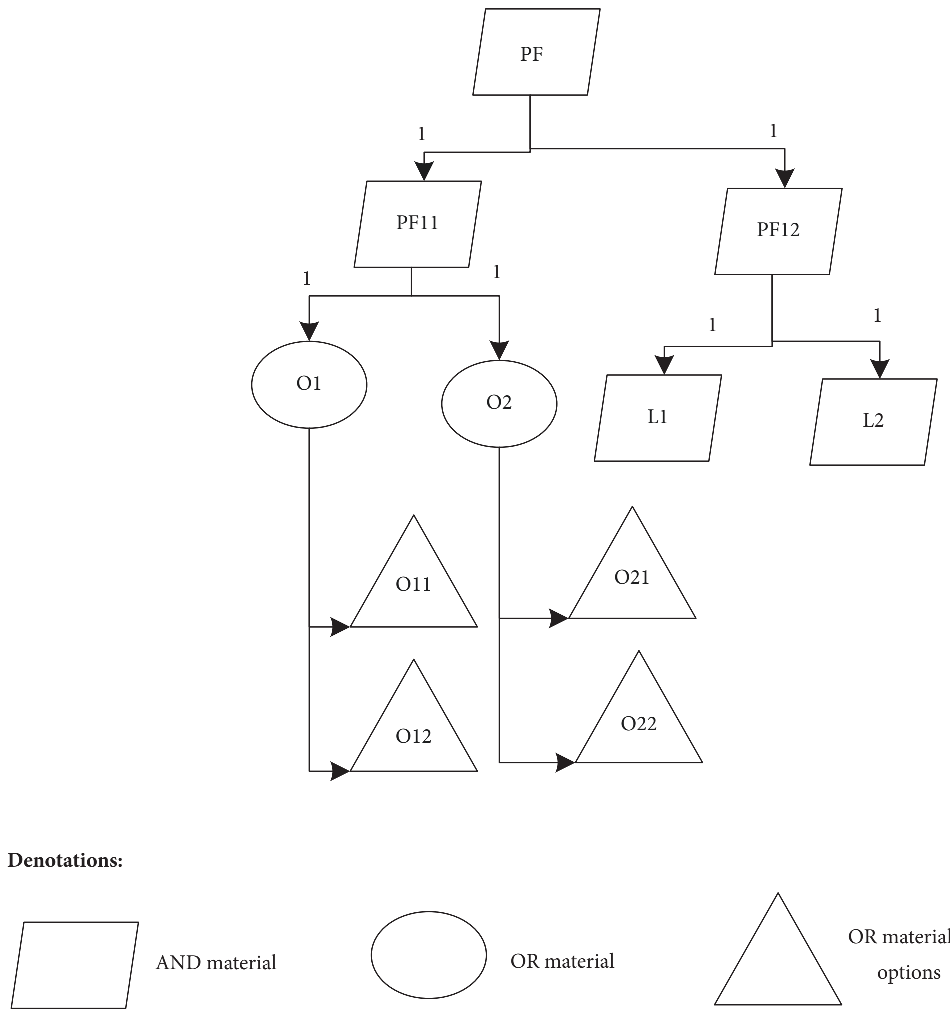

Figure 3: Generic bill of material for ready-to-eat food product.

Table 2: Supplier's performance rating with respect to product safety criteria.

Suppliers	Materials					
	O11	O12	O21	O22	L1	L2
1	[1.90,3.64]	[2.36, 3.83]	N/A			
2	[3.06, 4.47]	[3.75, 4.89]	N/A			
3	[3.17, 4.49]	[3.24, 4.72]	N/A			
4	[4.69, 5.97]	[5.04, 6.48]	N/A			
5	N/A		[2.28, 3.82]	[1.88, 3.61]	N/A	
6	N/A		[2.96, 4.35]	[2.96, 4.46]	N/A	
7	N/A		[3.23, 4.60]	[3.82, 4.94]	N/A	
8	N/A		[4.70, 5.97]	[5.22, 6.52]	N/A	
9	N/A		N/A		N/A	[3.45, 4.68]
10	N/A		N/A		N/A	[3.75, 4.89]
11	N/A		N/A		N/A	[3.82, 4.94]
12	N/A		N/A		[4.82, 6.01]	N/A
13	N/A		N/A		[5.04, 6.48]	N/A
14	N/A		N/A		[6.78, 8.79]	N/A

Note. N/A = this material is not available from supplier.

Table 3: Demand of products at various customer zones (1000 units).

Customer zones	Customer 1			Customer 2			Customer 3		
Period	P1	P2	P3	P1	P2	P3	P1	P2	P3
Product variant 1	[13, 14]	[11, 12]	[13, 14]	[10, 11]	[10, 11]	[11, 12]	[10, 11]	[11, 12]	[10, 11]
Product variant 2	[10, 11]	[13, 14]	[14, 15]	[12, 13]	[11, 12]	[12, 13]	[11, 12]	[10, 11]	[10, 11]
Product variant 3	[12, 13]	[14, 15]	[12, 13]	[12, 13]	[12, 13]	[10, 11]	[10, 11]	[10, 11]	[11, 12]
Product variant 4	[12, 13]	[10, 11]	[13, 14]	[11, 12]	[11, 12]	[11, 12	[11, 12]	[11, 12]	[10, 11]

Table 4: Price of OR materials ($/unit).

Suppliers/ Periods	OR Material					
	O11			O12		
	P1	P2	P3	P1	P2	P3
Supplier 1	[0.50,0.65]	[0.55,0.65]	[0.65,0.75]	[0.70,0.75]	[0.75,0.85]	[0.80,0.85]
Supplier 2	[0.55,0.60]	[0.65,0.75]	[0.60,0.65]	[0.75,0.80]	[0.75,0.85]	[0.85,0.90]
Supplier 3	[0.65,0.70]	[0.60,0.65]	[0.65,0.75]	[0.75,0.80]	[0.80,0.85]	[0.85,0.90]
Supplier 4	[0.65,0.70]	[0.65,0.75]	[0.70,0.75]	[0.78,0.85]	[0.83,0.85]	[0.88,0.90]
Suppliers/ Periods	OR Material					
	O21			O22		
	P1	P2	P3	P1	P2	P3
Supplier 5	[0.73,0.75]	[0.75,0.80]	[0.75,0.85]	[0.25,0.34]	[0.28,0.35]	[0.30,0.40]
Supplier 6	[0.75,0.80]	[0.78,0.80]	[0.75,0.85]	[0.29,0.29]	[0.30,0.30]	[0.32,0.40]
Supplier 7	[0.75,0.75]	[0.79,0.80]	[0.85,0.85]	[0.29,0.34]	[0.30,0.35]	[0.35,0.40]
Supplier 8	[0.80,0.85]	[0.83,0.87]	[0.87,0.90]	[0.30,0.35]	[0.35,0.40]	[0.38,0.42]

Table 5: Price of AND materials ($/unit).

Suppliers/ Periods	AND materials					
	L1			L2		
	P1	P2	P3	P1	P2	P3
Supplier 9		N/A		[0.30,0.35]	[0.33,0.35]	[0.35,0.40]
Supplier 10		N/A		[0.35,0.40]	[0.35,0.40]	[0.40,0.45]
Supplier 11		N/A		[0.35,0.40]	[0.40,0.45]	[0.45,0.50]
Supplier 12	[0.40,0.45]	[0.43,0.50]	[0.50,0.55]		N/A	
Supplier 13	[0.53,0.63]	[0.55,0.65]	[0.60,0.70]		N/A	
Supplier 14	[0.630.65]	[0.65,0.70]	[0.70,0.75]		N/A	

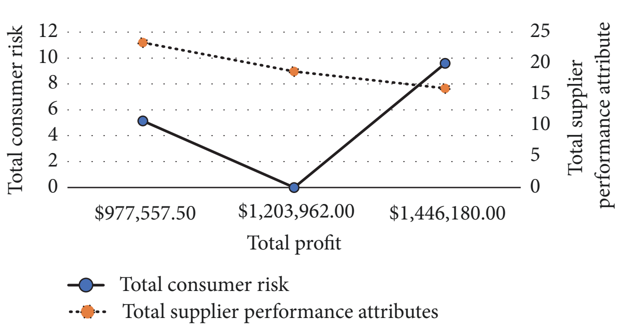

Figure 4: Tradeoff between model objectives.

head-to-head comparisons. The following conclusions are drawn from these solutions:

(1) If an organization wants to maximize the profit while completely ignoring the other two objectives, then supplier with least offered price should be selected and order quantity is allocated accordingly.

(2) Least number of possible production setups should be used for maximizing total profit.

(3) If an organization wants to minimize the total consumer risk than small production batches should be produced. This helps in minimizing chain dispersion and ultimately least number of consumers will be affected in case of a product recall.

(4) Finally, total supplier performance attribute can be increased by only selecting the highest rated suppliers from available supplier pool.

Table 6: Production and setup costs of various product variants.

Product Variant	Production cost ($/unit)	Setup cost ($/setup)
PV1	[0.80, 1.0]	[200, 300]
PV2	[1.0, 1.20]	[200, 300]
PV3	[0.80, 0.90]	[200, 300]
PV4	[0.70, 0.80]	[200, 300]

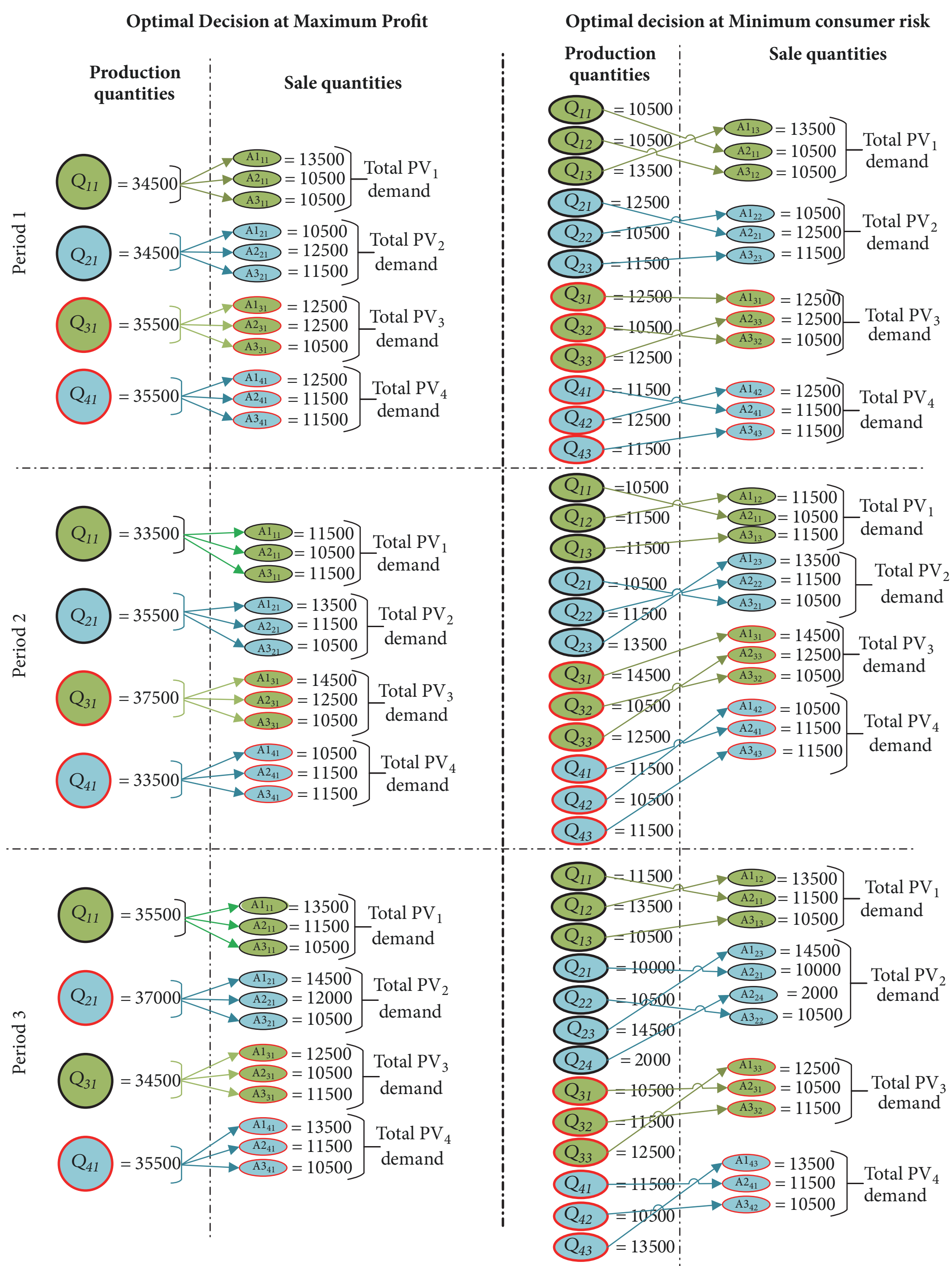

Figure 5: Head-to-Head comparisons between optimal profit and optimal consumer risk.

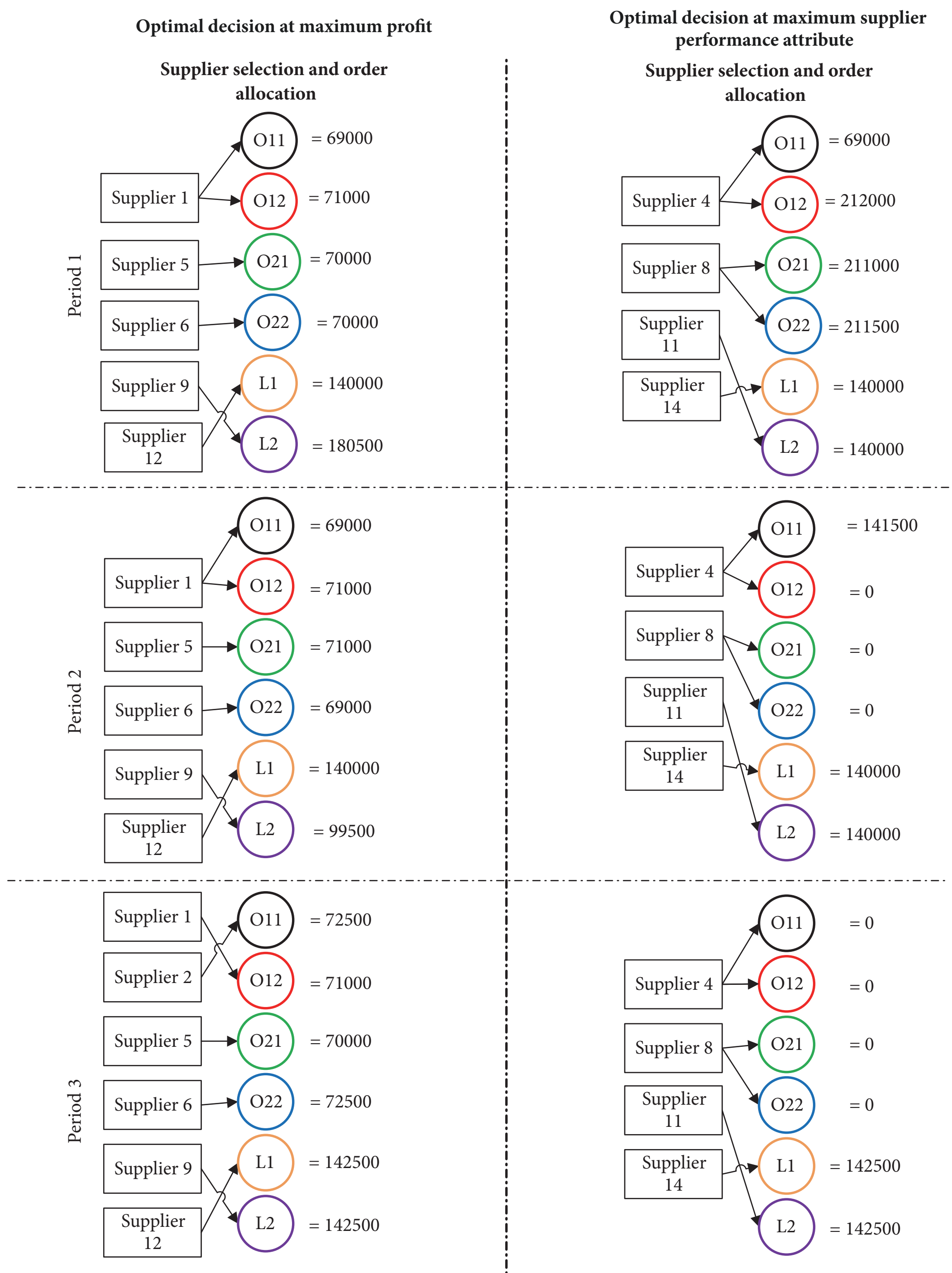

FIGURE 6: Head-to-Head comparisons between optimal profit and optimal supplier performance attribute.

Table 7: Materials and finished products holding costs.

Material/Product	Holding costs ($/unit)
O11	[0.50,0.60]
O12	[0.50,0.60]
O21	[0.30,0.40]
O22	[0.20,0.40]
L1	[0.30,0.50]
L2	[0.50,0.70]
PV1	[1.20,1.80]
PV2	[1.0,1.50]
PV3	[0.90,1.0]
PV4	[0.80.0.90]

After obtaining the pay-off values, the positive ideal solution (PIS) and negative ideal solution (NIS) are established. PIS for total profit = $1446180, total consumer risk = 0, and total suppliers performance = 23.313, whereas NIS for total profit = 977557.50, total consumer risk = 9.585, and total suppliers performance = 15.964. The fuzzy membership function of model objectives are established as follows:

$$\mu_{TP} = \begin{cases} 0, & \text{If } TP \leq 977557.50 \\ \dfrac{TP - 977557.50}{1446180 - 977557.50}, & \text{If } 977557.50 < TP < 1446180 \\ 1, & \text{If } TP \geq 1446180 \end{cases}$$

$$\mu_{TSPA} = \begin{cases} 0, & \text{If } TSPA \leq 15.964 \\ \dfrac{TSPA - 15.964}{23.313 - 15.964}, & \text{If } 15.964 < TSPA < 23.313 \\ 1, & \text{If } TSPA \geq 23.313 \end{cases} \quad (56)$$

$$\mu_{TCR} = \begin{cases} 1, & \text{If } TCR \leq 0 \\ \dfrac{9.585 - TCR}{9.585 - 0}, & \text{If } 0 < TCR < 9.585 \\ 0, & \text{If } TCR \geq 9.585 \end{cases}$$

After establishing fuzzy membership functions, the model is solved using the developed GWECON method. Optimal solutions obtained using proposed solution methods are given in Table 11.

5.2. Sensitivity Analysis. Sensitivity analysis of the proposed model and solution methodology is performed. Sensitivity analysis serves a number of goals in this research: it provides insight into the behaviour of supply chain based on model input parameter and solution methods' control parameters. It is necessary to analyze the impact of whitenization weight (α) on the final solution. Furthermore, solution methods control parameters may also have a significant impact on the final decision. Table 12 shows the sensitivity analysis report at various α values with $\varepsilon_1 = 0.5$ and $\varepsilon_2 = 0.5$. Assumed that DMs are satisfied with α between 0.4 and 0.5. The final solution can be obtained by gradually altering the values of ε_1 and ε_2. Table 13 shows the optimal solutions with α between 0.4 and 0.5. Graphical representation of the achievement level of

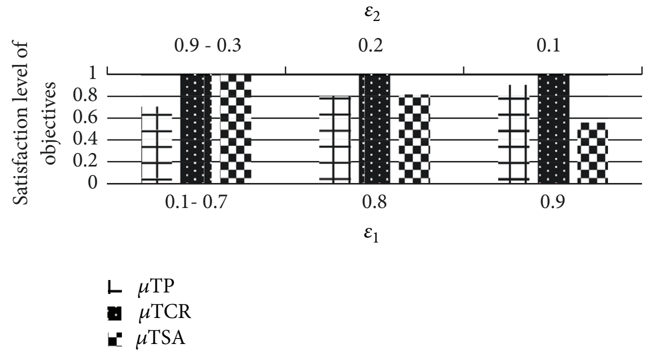

Figure 7: Satisfaction level of objective at $\alpha = 0.4$ using GWECON method.

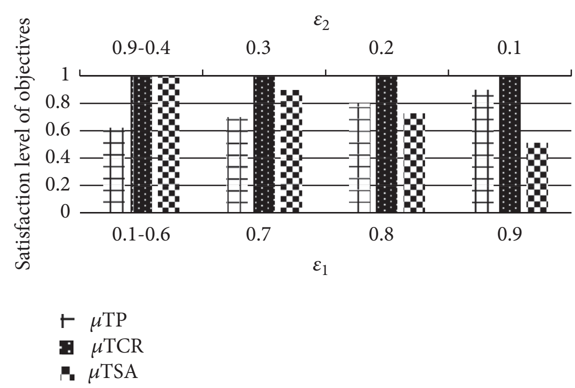

Figure 8: Satisfaction level of objective at $\alpha = 0.5$ using GWECON method.

model objectives at α equal to 0.4 and 0.5 is shown in Figures 7 and 8, respectively.

Assume that DMs preferred solution at $\alpha = 0.5$, $\varepsilon_1 = 0.7$, and $\varepsilon_2 = 0.3$ as shown in 5th row in Table 13. At this solution, profit objective is 70% achieved whereas achievement of suppliers' performance attribute objective is 89.79% and consumer risk objective is 100% achieved. Figure 9 shows the final decision based on DMs preference (i.e., at $\alpha = 0.5$, $\varepsilon_1 = 0.7$, and $\varepsilon_2 = 0.3$).

6. Conclusion

This study develops an integrated model for supplier selection and production-distribution planning considering product safety risks. This research takes advantage of grey systems theory to tackle the stochastic and recognitive uncertainties associated with the discussed problem. The advantage of using grey systems theory over stochastic and fuzzy theory is that grey systems theory requires neither a large set of data points nor robust membership function. The aim of proposed integrated model is to (1) select suitable suppliers based on predetermined criteria and allocate optimal purchase quantities, (2) optimally produce and dispatch the batches of finished products to consumers such that total consumer risk due to product safety issues should be minimum, and

Table 8: Probability of recall for product variants in terms of grey linguistic variables.

Product Variant	DM1		DM2		DM3		AGN
PV1	VU	[0.1,0.3]	U	[0.3,0.4]	EC	[0.4,0.5]	[0.23,0.39]
PV2	U	[0.3,0.4]	VU	[0.1,0.3]	U	[0.3,0.4]	[0.21,0.36]
PV3	VU	[0.1,0.3]	U	[0.3,0.4]	VU	[0.1,0.3]	[0.14,0.33]
PV4	VU	[0.1,0.3]	VU	[0.1,0.3]	U	[0.3,0.4]	[0.14,0.33]

Note. VU = very unlikely; U = unlikely; EC = even chance; AGN = aggregated grey number.

Table 9: Importance of objectives in terms of grey linguistic variables.

Objectives	Decision Maker						AGN
	DM1		DM2		DM3		
Profit	L	[0.1,0.3]	ML	[0.3,0.4]	L	[0.1,0.3]	[0.1442,0.3302]
TCR	MH	[0.5,0.6]	H	[0.6,0.9]	VH	[0.9,1.0]	[0.6463,0.8143]
TSA	ML	[0.3,0.4]	M	[0.4,0.5]	H	[0.6,0.9]	[0.4160,0.5646]

Table 10: Payoff values of model objectives.

Objective	Total profit ($)	Total consumer risk	Total Suppliers performance
Maximize Profit	1,446,180.00	9.585	15.964
Minimize Consumer risk	1,203,962.00	0.000	18.675
Maximize Suppliers performance attribute	977,557.50	5.150	23.313

Table 11: Optimal solution using proposed solution methods.

Method	μ_{TP}	μ_{TCR}	μ_{TSA}	TP	TCR	TSA
GWECON	0.6225	1.00	0.9954	1,269,258.00	0.00	23.2791

$\alpha = 0.5$, $\varepsilon_1 = 0.6$, $\varepsilon_2 = 0.4$.

Table 12: Sensitivity analysis of GWECON.

α	μ_{TP}	μ_{TCR}	μ_{TSA}	TP	TCR	TSA
0.1	0.6490	1.0000	0.9958	1252214.00	0.00	25.5937
0.2	0.6418	1.0000	0.9956	1256825.00	0.00	25.0151
0.3	0.5079	1.0000	0.9954	1261203.00	0.00	24.4364
0.4	0.7057	1.0000	0.9953	1265347.00	0.00	23.8577
0.5	0.6225	1.0000	0.9954	1269258.00	0.00	23.2791
0.6	0.6087	1.0000	0.9950	1272935.00	0.00	22.7004
0.7	0.5939	1.0000	0.9949	1276149.00	0.00	22.1218
0.8	0.5197	1.0000	0.9950	1279589.00	0.00	21.5431
0.9	0.5684	1.0000	0.9947	1282566.00	0.00	20.9645

Table 13: Optimal solution using GWECON at selected α range.

α	ε_1	ε_2	μ_{TP}	μ_{TCR}	μ_{TSA}	TP	TCR	TSA
0.4	0.1- 0.7	0.9 - 0.3	0.7057	1.00	0.9953	1,265,347.00	0.00	23.8577
	0.8	0.2	0.8000	1.00	0.8136	1,322,312.00	0.00	22.5822
	0.9	0.1	0.9000	1.00	0.5596	1,382,690.00	0.00	20.7987
0.5	0.1-0.6	0.9-0.4	0.6225	1.00	0.9954	1,269,258.00	0.00	23.2791
	0.7	0.3	0.7000	1.00	0.8979	1,305,593.00	0.00	22.5628
	0.8	0.2	0.8000	1.00	0.7280	1,352,456.00	0.00	21.3139
	0.9	0.1	0.9000	1.00	0.5121	1,399,318.00	0.00	19.7275

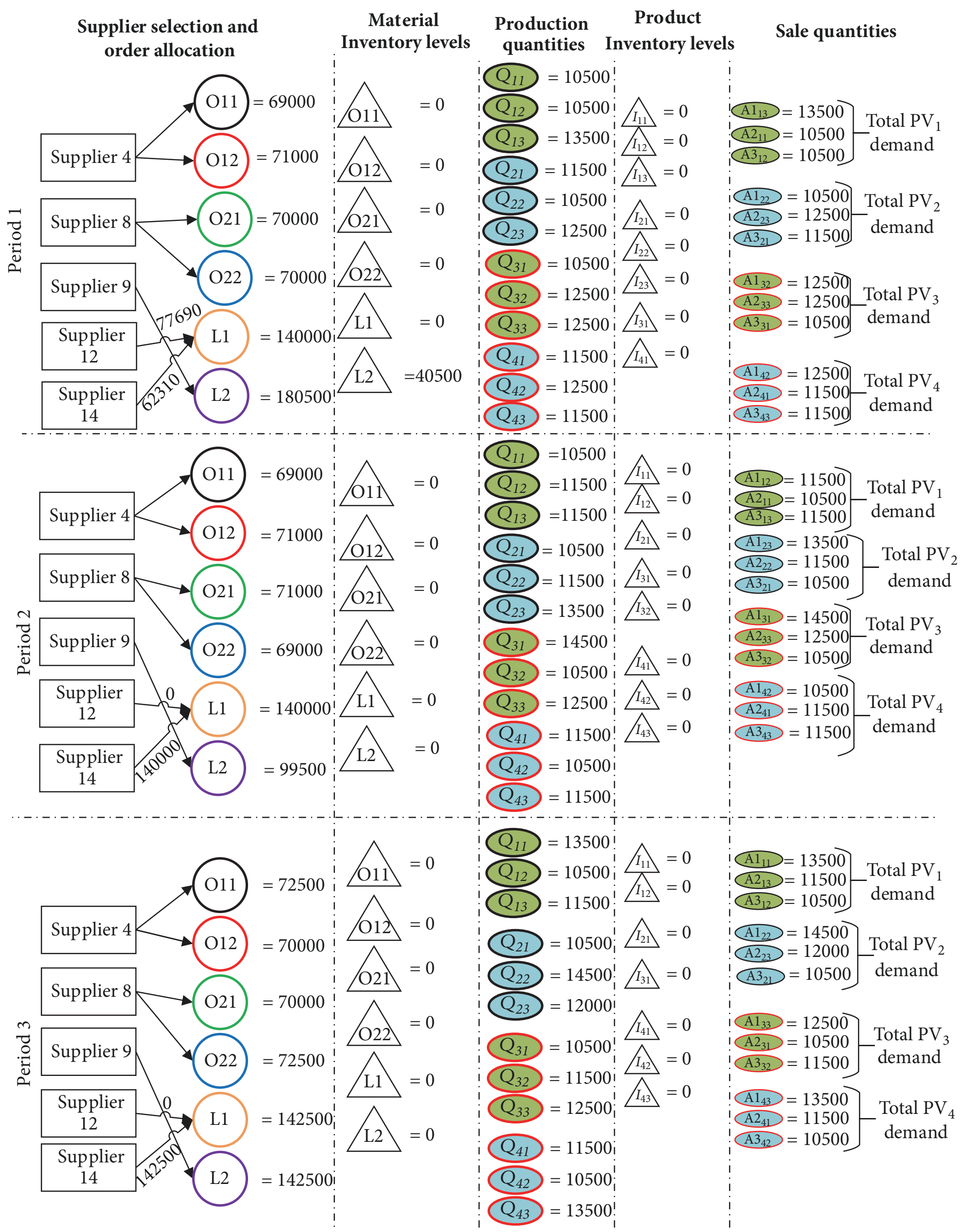

Figure 9: Final solution at DMs preferred choice using GWECON method.

(3) efficiently manage the raw material and finished product inventories over planning periods. Finally, a grey-fuzzy multiobjective solution methodology is developed to solve the proposed integrated model. For this purpose, the grey-weighted ε-constrained method (GWECON) is developed to solve the grey multiobjective problem.

Limitations of this study are worth noting. First, the generalization of our results may be limited because of research setting. This paper shows the application of the proposed integrated model in food product manufacturing; we believe future research in any other product manufacturing will contribute to the literature. Second, this research utilizes the concept of chain dispersion to estimate the consumer risks; it will be valuable to develop other metrics for consumer risks due to product safety such as time to recall. Third, we assumed equal expertise of DMs for finalizing importance of objectives, whereas, in practice, DMs may have different expertise level and it may have some impact on the final decision. Therefore, for future research, weighted criteria based on expertise level may be developed. In the future, the proposed model can be extended to consider batch and chain dispersion concepts simultaneously. Also, it will be valuable to apply a grey-weighted ε-constrained method in other research areas of supply chain multiobjective optimization problems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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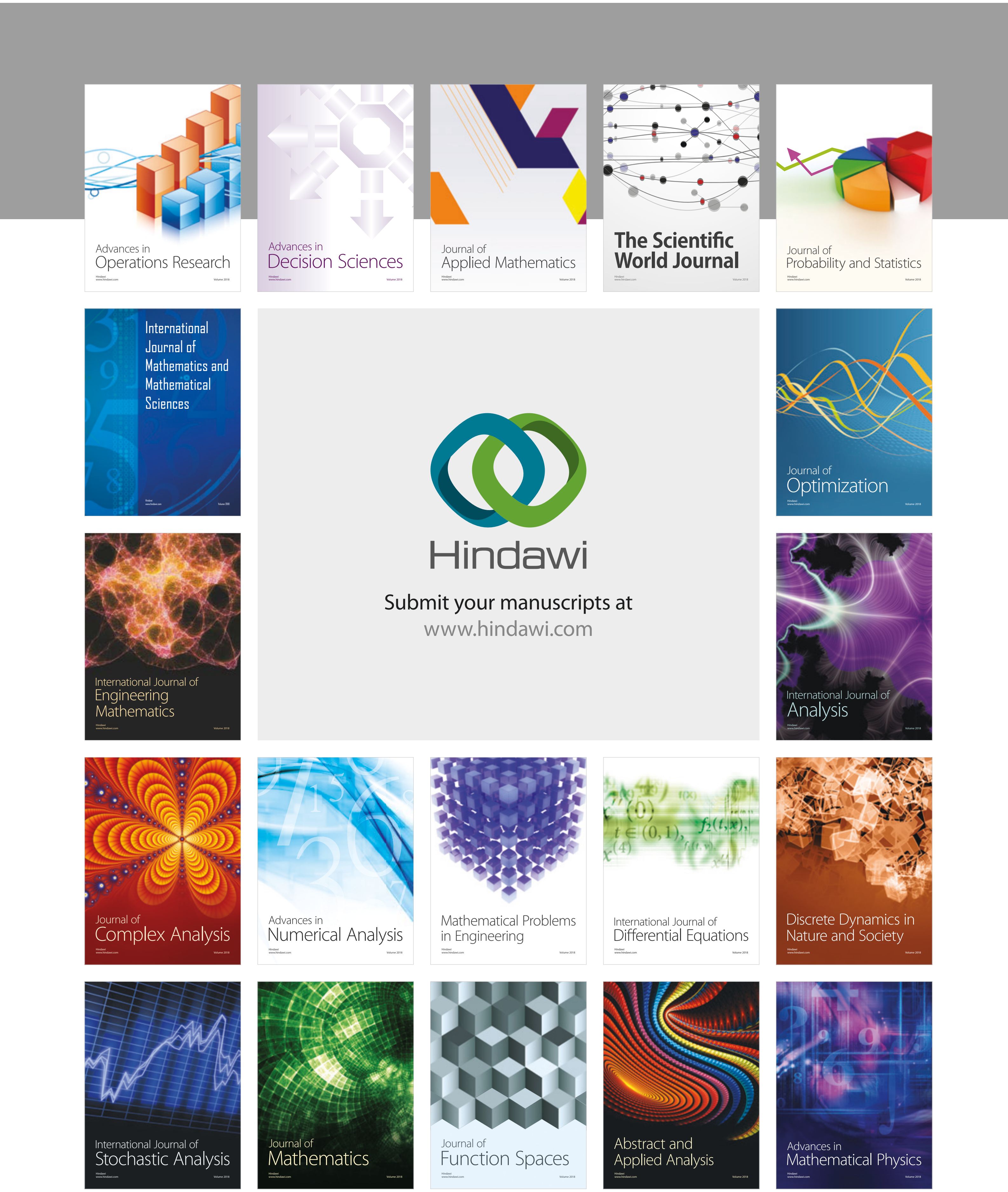
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