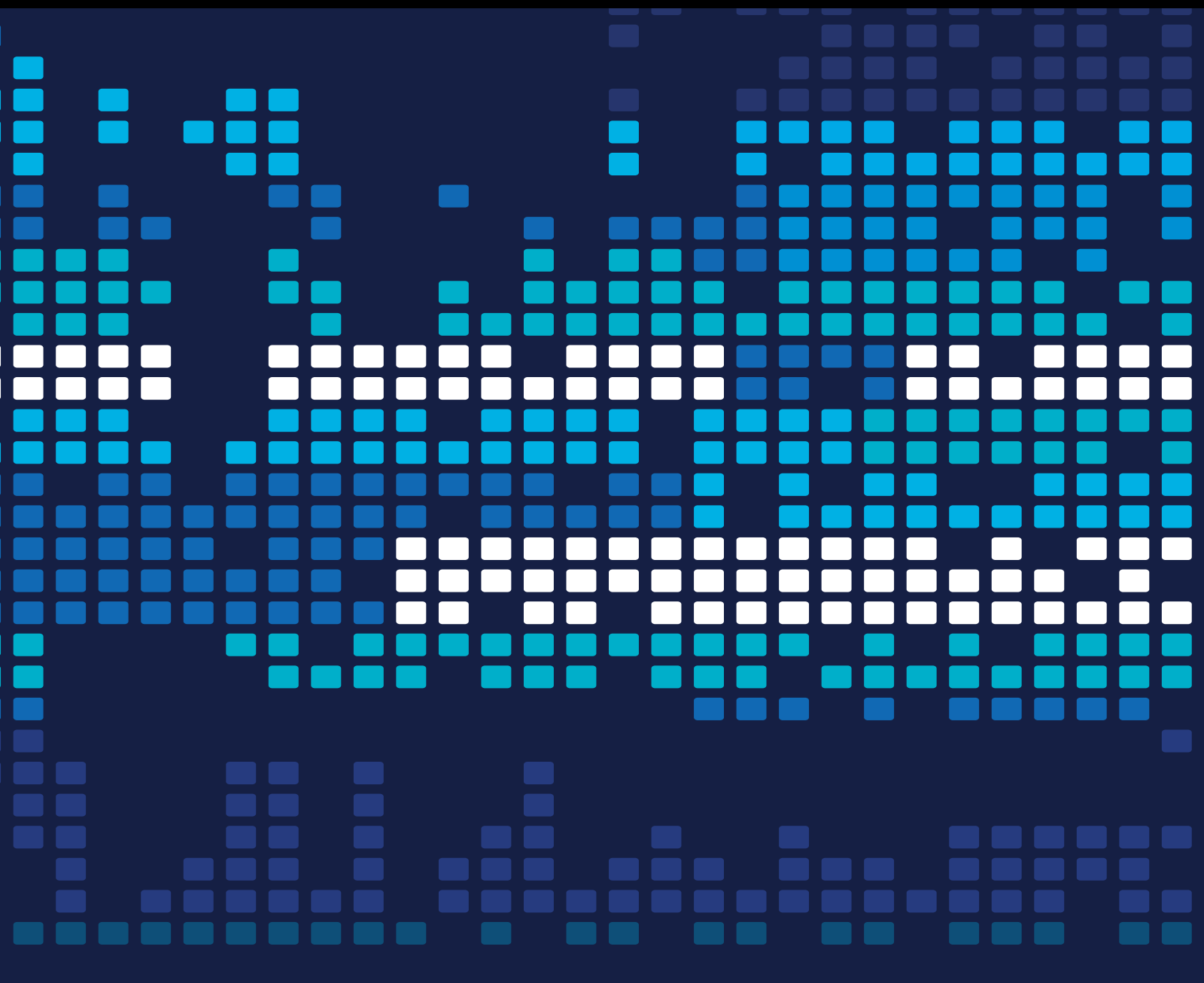
Scientific Programming

Uncertain Decision-Making: A Mathematical Programming Perspective

Guest Editors: Xiang Li, Dan Ralescu, Xiaofeng Xu, Lei Li, and Irene Diaz



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Editorial

Uncertain Decision-Making: A Mathematical Programming Perspective

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Uncertain decision exists in various kinds of human behaviors, especially in coping with complex problems. There is no surprise that with the ever-increasing complexity of problems, uncertain decision will be made by different formal ways and technologies in dynamic environment, and it calls for innovative approaches to provide interpretable solutions and effective decisions. Mathematical programming with its broad ornamentation of technologies of linear programming, nonlinear programming, integer programming, uncertain programming, combinatorial optimization, and so on plays an important role in the formulating and solving uncertain problems.

This special issue aims to deliver a platform. On the platform, researchers coming from academe and industry can present the advanced methodologies to cope with uncertain decision-making and optimization problems. At the same time, they can also elaborate on the state-of-the-art case studies in selected areas of application through the usage of concepts of mathematical programming and reports on the linkages between methodology and practice of mathematical programming.

Once the call for papers was announced in February 2016, this special issue has attracted tremendous attention. In total, we received 46 manuscripts. After a rigorous review process, 18 papers have been finally accepted for publication.

To gain a better insight into the essence of the special issue, we offer brief highlights of the contributing papers.

Theory. The paper titled "Model and Simulation of Network Crisis Information Diffusion under Uncertain Environment" views the public as a series of cellular automata and sets up some cellular state evolution rules and then explores the diffusion rule of crisis information diffusion process and finds out the key factors of crisis information diffusion process and its influence on the diffusion scale and effect. A panel threshold model is used in "Noninterest Income and Performance of Commercial Banking in China" with balanced panel dataset of 16 listed Chinese commercial banks, for the period of 2007 to 2013, to investigate the relationship between noninterest income and performance. X. N. Zhang et al. established an evaluation index system for the regional collaborative innovation system considering the uncertainty of collaborative systems. The collaborative uncertainty decision model is constructed to determine the regional innovation system's collaborative innovation effectiveness. The paper titled "Modified Bat Algorithm Based on Lévy Flight and Opposition Based Learning" proposes an improved BA called OBMLBA. In the proposed algorithm, a modified search equation with more useful information from the search experiences is introduced to generate a candidate solution. Furthermore, the concept of opposition based learning (OBL) is embedded to BA to enhance the diversity and convergence capability. The paper written by H. Zhang et al. summarizes the factors that affect the city logistics distribution system. Starting from the research of factors that

influence the reliability of city distribution system, further construction of city distribution system reliability influence model is built based on Bayesian networks. The complex problem is simplified by using the sub-Bayesian network, and an example is analyzed. The paper titled "Dependent-Chance Goal Programming for Water Resources Management under Uncertainty" introduces a new tool-uncertainty theory to deal with such uncertainty which is treated as uncertain variable with uncertainty distribution. And a dependent-chance goal programming (DCGP) model is provided for water resources management under such circumstance. J. Song et al. analyze economy-energy-environment system's structure and components. G. Yang and H. Gao put forward an evaluation model of the uncertain risks of knowledge management. Based on set pair theory, a model is established to identify the knowledge management risk. Through the concept of connection number, knowledge management risk is divided into five levels.

Methodologies and Case Studies. X. Xu et al. in the paper entitled "Resource Allocation Optimization Model of Collaborative Logistics Network Based on Bilevel Programming" consider the uncertainty of time to establish a bilevel programming model with random constraints and propose a genetic simulated annealing hybrid intelligent algorithm to solve it. X. Shan et al. present a practical risk assessment method based on Bow-Tie model and Bayesian network for risk analysis of natural gas pipeline leakage. Q. Meng et al. propose a decision method for maximizing service quality in machinery industry under budget constraints, from the perspective of enterprise capacity and customer satisfaction. They formalize the relationship between customer satisfaction and sufficiency of service quality elements quantitatively and develop a novel nonlinear programming model to maximize service quality under budget constraints. X. Gong and J. Lu investigate spillovers in the Capesize forward freight agreements (FFAs) markets before and after the global financial crisis. The results suggest that there are volatility spillover effects in certain Capesize FFAs routes, and the effects from spot rates to FFAs take place before crisis, yet they are bilateral after crisis. J. Liu et al. present an integrated method to assess the supply chain vulnerability. Combining the fuzzy theory and the gray theory, the correlation degree of each vulnerability indicator can be calculated and the target improvements can be carried out. In order to verify the effectiveness of the proposed method, they use Kendall's tau coefficient to measure the effect of different methods. S. C. Lu et al. build two competitive theory models. Through analyzing the equilibrium, one gets two main results: (1) according to different service area, the cities (Dalian and Tianjin) should have different price; (2) the two-sided market characters have an impact on their strategies. The paper titled "Optimal Uncertainty Decision of Innovation Products Output Based on Return Collection" studies the optimal single-period production decision between reused parts and conventional new parts in complementary and substitute relationships. It further gives the analytical expressions for satisfying the optimal production and provides some numerical examples. A bilevel fuzzy chance constrained model is developed in "Bilevel Fuzzy Chance Constrained Hospital Outpatient Appointment Scheduling Model" to solve the hospital outpatient appointment scheduling problem based on revenue management. Then use chance operator to handle the model with fuzzy parameters and equivalently transform the appointment scheduling model into a crisp model. Moreover, interactive algorithm based on satisfaction is employed to convert the bilevel programming into a single level programming, in order to make it solvable. Li et al. developed a novel multiobjective optimization model with mixed uncertain coefficients, which maximizes the total profits and minimizes the percentage of items delivered late, percentage of items rejected, and total loss cost due to supplier dysfunction.

We envision that the papers published in this special issue would be of interest to researchers and practitioners and help identify further research directions. We also hope that the readers can find the material of this special issue both interesting and inspiring when exploring the field of optimization under uncertainty.

Acknowledgments

As Guest Editors, we would also like to thank all the referees for their support and professional service and express the gratitude to all authors for their submissions to this special issue. Without the support of the authors and the referees, it would have been impossible to make this special a reality.

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Research Article

Resource Allocation Optimization Model of Collaborative Logistics Network Based on Bilevel Programming

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Collaborative logistics network resource allocation can effectively meet the needs of customers. It can realize the overall benefit maximization of the logistics network and ensure that collaborative logistics network runs orderly at the time of creating value. Therefore, this article is based on the relationship of collaborative logistics network supplier, the transit warehouse, and sellers, and we consider the uncertainty of time to establish a bilevel programming model with random constraints and propose a genetic simulated annealing hybrid intelligent algorithm to solve it. Numerical example shows that the method has stronger robustness and convergence; it can achieve collaborative logistics network resource allocation rationalization and optimization.

1. Introduction

Collaborative logistics network is a supply and demand network, which consists of supply collaboration nodes such as raw materials and equipment and logistics function collaboration nodes such as transportation and warehousing and even road and relationship between nodes [1]. The allocation of resource is to meet the supply and demand network. The aim is to collaborate logistics network enterprise internal and external resources and combine the supply chain system effectively which is composed of producers, manufacturers, and customers to realize the lowest cost and the best quality service [2]. So, reasonable resource allocation process is the basis to realize the orderly operation of the whole logistics network. However, collaborative logistics network has suppliers, transit warehouses, vendors, and other forms of logistics node and has some characteristics such as being dynamic, open, and complex. It leads to some uncertainty factors in the process of allocating logistics resources that may have an effect on the running time and operating cost. Therefore, this research about resource allocation of collaborative logistics network is how to select nodes in the numerous suppliers and transit warehouse under the condition of considering the influence of uncertainty factors to realize the optimal logistics system.

The current research on collaborative logistics network resource scheduling is not enough in depth and it is mainly concentrated in the delivery path optimization and distribution address selection as well as the relationship between collaboration node and so forth. In terms of path selection, Yu et al. [3] established a scheduling model with time as constraint and the shortest route as object and used artificial intelligence algorithms to solve the problem. Najera [4] used evolutionary algorithm to study transportation routing problem in consideration of capacity of vehicle. Mir and Abolghasemi [5] took vehicle transportation situations of encoring or not into account and proposed the optimal route according to the customer location changes. Chen et al. [6] made full use of geographic information system technology to select path under the constraint of the least distribution sites. In terms of optimal location selection, Cheng et al. [7] study the impact of the rapid transit on the capacity of current urban transportation system, and a two-mode network capacity model, including the travel modes of automobile and transit, is developed based on the well-known road network capacity model. Turskis and Zavadskas [8] used the fuzzy multiple criteria decision to describe fuzziness of site selection of distribution center. Nozick and Turnquist [9] established a location optimization decision model from the aspects of cost and customer responsiveness.

Yang and Zhou [10] built the location selection model with equilibrium constraints considering facility competition on the basis of the equilibrium theory and then applied genetic algorithm and projection algorithm to solve the model. For the relationship between collaboration points, Qiu and Wang [11] develop a robust optimization model for designing a three-echelon supply chain network that consists of manufacturers, distribution centers, and retailers under both demand uncertainty and supply disruptions. Liu et al. [12] considered three-layer logistics service supply chain and studied the order task allocation model between collaboration nodes.

Integrating the documents, we can find that the current research focused on the microscopic aspects, such as path optimization and site selection and used artificial intelligence algorithm to solve the model. But the ideal model cannot fully describe the collaborative allocation of resources due to the network's complexity and some uncertainty factors in the process of resource allocation. Collaborative logistics network resource allocation process involves three levels, which are suppliers, transit warehouse, and vendors, so the bilevel programming model can be used to explain the relationship between every two levels of nods. At the same time, the stochastic constrained programming can protect model against uncertain influence, and it has been applied to the system dynamics, structural dynamics, and financial and other fields [13–15]. Therefore, this article will set up the three-level nodes relationship among the suppliers, transit warehouses, and retailers and establish a bilevel programming model with chance constrained to control uncertainty factors, so as to make the whole logistics network system optimal under meeting the nodes' profit of both sides.

Generally speaking, the bilevel programming is NP-hard problem, Ben-Ayed and Blair (1988) have proved that [16] this problem does not have a polynomial algorithm, so the solution of it is very complicated. Like genetic algorithm (GA) and Simulated Annealing Algorithm (Simulated Annealing, SA), Neural Network Algorithm (NNA), and so forth, some intelligent algorithms were used to solve the bilevel programming problem. Li et al. [17] put forward a genetic algorithm that can effectively solve bilevel programming problem. In this method, they used constraint to transform bilevel problem into a single-level one and designed the binary coding to solve the multiplier, and numerical experiment shows that the given algorithm can find the global optimal solution in the least time. Niwa et al. [18] proposed a bilevel programming problem that the upper class has only one decision-maker while the lower one has multiple decision-makers and a distribution of the genetic algorithm. Li and Wang [19] studied a special kind of linear quadratic bilevel programming problems, and genetic algorithm was proposed after being converted into equivalent problem.

Genetic algorithm by the ideas of the fittest in nature chooses an optimal individual for the solution of the model by selection, crossover, and mutation genetic operation. Although it has some characteristics such as simple operation, strong operability, and problem space independence, it is easy to exhibit slow convergence speed and get only local optimal value [20]. Simulated annealing algorithm is the result of logistics annealing principle of solid matter, starting from an initial temperature to find the optimal solution in the solution space with the reduction of the temperature parameters. Although it can get the global optimal solution, it evolved slowly and has strong dependence on parameters [21]. So there are advantages and disadvantages, respectively, of the two algorithms, hybrid genetic simulated annealing algorithms can compensate deficiency for each other, they not only can search the related areas of optimal solution in the global but also can find the optimal solution in the region of the optimal solution, and there have been some scholars who have done the related research. Wang and Zheng [22] proposed a hybrid heuristic algorithm, the algorithm mixed the genetic algorithm and simulated annealing method and the sampling process of simulated annealing method instead of mutation operators of genetic algorithm, and this algorithm improves the local search ability of genetic algorithm. Wang et al. [23] assume that the drivers all make route choices based on Stochastic User Equilibrium (SUE) principle. Two methods, that is, the sensitivity analysis-based method and genetic algorithm (GA), are detailedly formulated to solve the bilevel reserve capacity problem. Kong et al. [24] establish a bilevel programming model of land use structure indexes variables and use GASA to solve the problem, and land and road area ratio should be improved by numerical example results. So in this paper designing the combination of genetic and simulated annealing hybrid algorithm, to solve the bilevel programming problem, is feasible.

2. Considering Uncertainty Resource Deployment of Bilevel Programming Model

2.1. Bilevel Programming Model. Bilevel programming (BP) [25] model was presented by Bracken and McGill in 1973, the lower decision-maker makes decision in the first place, the upper policymakers must predict the possible reaction of the lower ones, and then the lower one reacts according to the decision of the upper one to optimize the objective function of the individual. The general model is

$$\begin{aligned} \min_{x \in X} \quad & F(x, y) \\ \text{s.t.} \quad & G(x, y) \leq 0, \\ \min_{y \in Y} \quad & f(x, y) \\ \text{s.t.} \quad & g(x, y) \leq 0. \end{aligned} \tag{1}$$

Among them, $x \in R^{n_1}$ and $y \in R^{n_2}$. The upper variable is $x \in R^{n_1}$, and the lower variable is $y \in R^{n_2}$. Also, the functions $F : R^{n_1} \times R^{n_2} \to R$ and $f : R^{n_1} \times R^{n_2} \to R$ are the upper and the lower objective function, respectively, and vector-valued functions $G : R^{n_1} \times R^{n_2} \to R^{m_1}$ and $g : R^{n_1} \times R^{n_2} \to R^{m_2}$ are, respectively, the upper and the lower constraint conditions.

2.2. Chance Constrained Programming Model. Chance Constrained Programming [26] is a method of stochastic programming put forward by Charnes and Cooper in 1959. It allows decision value within a certain range of fluctuations

considering the possibility that decision-making process may not meet the constraint conditions, but the probability of the constraint set-up must not be less than a certain confidence level α which is small enough. The general model is

$$\begin{aligned} \min \quad & Z(x) = \sum_{j=1}^{n} c_j x_j \\ \text{s.t.} \quad & \Pr\left[\sum_{j=1}^{n} a_{1j} x_j \geq b_1, \ldots, \sum_{j=1}^{n} a_{mj} x_j \geq b_m\right] \geq \alpha \\ & x_j \geq 0 \quad j = 1, 2, \ldots, n. \end{aligned} \tag{2}$$

Among them, Pr[ ] is the probability of the event set-up, α is the confidence probability for the condition, b_m are random variables that obey a certain distribution, and a and b obey $N(\mu_1, \sigma_1^2)$ and $N(\mu_2, \sigma_2^2)$, respectively.

2.3. The Model of Collaborative Logistics Network Resource Allocation considering Uncertainty. This paper researches on the resource allocation optimization decision of multiple suppliers and multiple warehouse transfer nodes and retailers. The raw materials price and transportation fee that each suppliers charge are different, and it is a key issue for the retailers to select the optimization suppliers and carry resources more effectively to their warehouses transfer node. At the same time, the retailers compare the transit fees cost of each warehouse, choosing the lowest one or more warehouses to allocation according to their own requirements, which need to focus on every step of the whole logistics network. This kind of relationship can be explained by bilevel programming model. Described in this paper, the upper programming's goal is how the suppliers realize the profit maximization of their own on the condition of meeting the warehouse requirements; the lower level programming describes the lowest cost during the process of warehouse transit center and retailer.

In order to understand better, we can use mathematical language to describe the problem as follows.

Assume that the logistics network N consists of suppliers $\{S_i \mid i = 1, 2, \ldots, n_i\}$, transit warehouses $\{M_j \mid j = 1, 2, \ldots, n_j\}$, retailers $\{P_k \mid k = 1, 2, \ldots, n_k\}$, and links between each node $\{R \mid R \in R_{S_iM_j} \cup R_{M_jP_k}\}$, including logistics nodes $\{O \mid O \in S \cup M \cup P\}$. When retailer P_k sends the demand quantity $D_l^{P_k}$ of resource $\{l \mid l = 1, 2, \ldots, n_l\}$, the resource will be transported to P_k from warehouses M_j. $X_{M_jP_k}^l$ stands for the quantity of products l that are distributed to the retailers P_k from the warehouses M_j; $X_{S_iM_j}^l$ stands for the quantity of raw materials that are distributed to the warehouses M_j from the suppliers S_i. $\{E(R) \mid E(R) \in E(R_{S_iM_j}) \cup E(R_{M_jP_k})\}$ stand for the distance between all logistics nodes. Due to the different location of logistics nodes, the product fees of transportation, storage, packaging, and processing for each unit are also different. Therefore, $\{C(R) \mid C(R) \in C(R_{S_iM_j}^l) \cup C(R_{M_jP_k}^l)\}$ stand for the cost of each unit distance between different logistics nodes to transport resources l; $C(f_O^l)$ and $C(g_O^l)$ stand for the unit cost of storage and processing (including labor) for all logistics nodes. Suppliers as the disclosing party, charge transit warehouses $C(X_{S_iM_j}^l)$ for the resources l. Considering that all logistic nodes have a certain amount of time requirement to order processing and distribution of resources, the times of delivery requirement from warehouses to retailers and supplies to warehouses, respectively, are $T_{M_jP_k}^l$ and $T_{S_iM_j}^l$, the times of order processing and production processing, respectively, are $T_{M_jP_k}^l{}'$, $T_{S_iM_j}^l{}'$, $T_{M_jP_k}^l{}''$, and $T_{M_jP_k}^l{}''$; transport vehicle maximum loading capacities, respectively, are $G_{M_jR_k}$ and $G_{S_iM_j}$.

In the process of research, the assumptions made are as follows for the purpose of simplified model:

(1) All land transportation is between all logistics nodes.

(2) The logistics node routes and distance have to be known and are fixed.

(3) Vehicle average speed is V during the process of transportation between various logistics nodes.

2.3.1. The Upper Programming considering the Relationship between Suppliers and Warehouse Transit Centers

$$\max F_1 = \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n}\sum_{i=1}^{n}\left(C\left(X_{S_iM_j}^l\right) - C\left(R_{S_iM_j}^l\right)E\left(R_{S_iM_j}\right) - C\left(f_{S_i}^l\right) - C\left(g_{S_i}^l\right)\right)X_{S_iM_j}^l u_i \tag{3}$$

$$\sum_{i=1}^{n} u_i \geq 1 \tag{4}$$

$$G_{S_iM_j} \geq X_{S_iM_j}^l \tag{5}$$

$$\Pr\left[T_{S_iM_j}^l{}' + T_{S_iM_j}^l{}'' + \frac{E\left(R_{S_iM_j}\right)}{V} \leq T_{S_iM_j}^l\right] = \alpha \tag{6}$$

$$u_i X_{S_iM_j}^l = X_{M_jP_k}^l \tag{7}$$

$$X^l_{S_iM_j} \geq 0 \quad i = 1, 2, \ldots, n, \ \ j = 1, 2, \ldots, n \tag{8}$$

$$u_i \in \{0, 1\}. \tag{9}$$

Among them, (3) is from the point of view of the suppliers, which is pursuing of the profit maximization; (4) ensures warehouse transit centers at least choose one supplier; (5) means the amount of resources that the suppliers provide cannot exceed its maximum of vehicle loading capacity; (6) stands for the probability that order processing time, processing time, and shipping time of supplies cannot exceed the longest time of warehouse transit centers which is α; (7) means the amount of resources that warehouse transit centers provide is equal to what all suppliers provide; (8) resource demand is a positive number; (9) is supplier's 0-1 variable constraints, which means that select supplier i has a value of 1 or a value of 0.

2.3.2. The Lower Programming considering the Relationships between Warehouse Transit Centers and Retailers

$$\begin{aligned} \min F_2 &= \sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{l=1}^{n}\sum_{j=1}^{n}\left(C\left(R^l_{M_jP_k}\right)E\left(R_{M_jP_k}\right) + C\left(f^l_{M_j}\right) + C\left(g^l_{M_j}\right)\right) \\ &\cdot X^l_{M_jP_k}u_j \end{aligned} \tag{10}$$

$$\sum_{j=1}^{n} u_j \geq 1 \tag{11}$$

$$\sum_{j=1}^{n}\sum_{k=1}^{n}\sum_{j=1}^{n} u_j X^l_{M_jP_k} \geq D^{P_k}_l \tag{12}$$

$$G_{M_jR_k} \geq X^l_{M_jP_k} \tag{13}$$

$$\Pr\left[T^l_{M_jP_k}{}' + T^l_{M_jP_k}{}'' + \frac{E\left(R_{M_jP_k}\right)}{V} \leq T^l_{M_jP_k}\right] = \beta \tag{14}$$

$$X^l_{M_jP_k} \geq 0 \quad j = 1, 2, \ldots, n, \ k = 1, 2, \ldots, n \tag{15}$$

$$u_j \in \{0, 1\}. \tag{16}$$

Among them, expression (10) stands for the warehouse transit center and distributors as a whole, pursuing the minimizing cost including transportation and storage and producing cost; (11) ensures that retailers choose at least one supply warehouse transit center; (12) means the total resources that product warehouse transit centers provide should meet the demand of retailers P_k; (13) means the amount of resources that warehouse transit centers provide cannot exceed its maximum of vehicle loading capacity; (14) stands for the probability that the order processing time, processing time, and shipping time of warehouse transit centers cannot exceed the longest time of retailers which is β; (15) means resource demand is a positive number; (16) is warehouse transit centers' 0-1 variable constraints, which means that chosen warehouse j has a value of 1 or value of 0.

3. The Solution to the Resource Allocation Bilevel Programming Model considering Uncertainty

3.1. Random Planning Constraints Transformation. As for the uncertain factors during transportation and order processing, we need to transform them into deterministic constraints. The solution method of stochastic programming constraint probably has two kinds: one is transforming the stochastic programming into a deterministic mathematical programming through certain changes and then using the existing method that solves the deterministic mathematical programming to solve; the other method is to use the intelligent algorithm such as neural network based on the idea of approximation function.

Due to solving bilevel programming after stochastic programming constraints transformation, we take the first method to research. The order processing times $T^l_{M_jP_k}{}'$ and $T^l_{S_iM_j}{}'$, respectively, obey the normal distributions $T^l_{M_jP_k}{}' \sim N(\mu(T^l_{M_jP_k}{}'), \sigma(T^l_{M_jP_k}{}')^2)$ and $T^l_{S_iM_j}{}' \sim N(\mu(T^l_{S_iM_j}{}'), \sigma(T^l_{S_iM_j}{}')^2)$; $T^l_{M_jP_k}{}''$ and $T^l_{S_iM_j}{}''$, respectively, obey the normal distributions $T^l_{M_jP_k}{}'' \sim N(\mu(T^l_{M_jP_k}{}''), \sigma(T^l_{M_jP_k}{}'')^2)$ and $T^l_{S_iM_j}{}'' \sim N(\mu(T^l_{S_iM_j}{}''), \sigma(T^l_{S_iM_j}{}'')^2)$; $E(R_{M_jP_k})/V$ and $E(R_{S_iM_j})/V$, respectively, obey the normal distributions $E(R_{M_jP_k})/V \sim N(\mu(E(R_{M_jP_k})/V), \sigma(E(R_{M_jP_k})/V)^2)$ and $E(R_{S_iM_j})/V \sim N(\mu(E(R_{S_iM_j})/V), \sigma(E(R_{S_iM_j})/V)^2)$.

So the stochastic programming constraint (7)

$$\Pr\left[T^l_{S_iM_j}{}' + T^l_{S_iM_j}{}'' + \frac{E\left(R_{S_iM_j}\right)}{V} \leq T^l_{S_iM_j}\right] = \alpha \tag{17}$$

can be transformed into

$$\begin{aligned} &\mu\left(T^l_{S_iM_j}{}'\right) + \phi^{-1}(\alpha)\,\sigma\left(T^l_{S_iM_j}{}'\right) + \mu\left(T^l_{S_iM_j}{}''\right) \\ &+ \phi^{-1}(\alpha)\,\sigma\left(T^l_{S_iM_j}{}''\right) + \mu\left(\frac{E\left(R_{S_iM_j}\right)}{V}\right) \\ &+ \phi^{-1}(\alpha)\,\sigma\left(\frac{E\left(R_{S_iM_j}\right)}{V}\right) \leq T^l_{S_iM_j} \end{aligned} \tag{18}$$

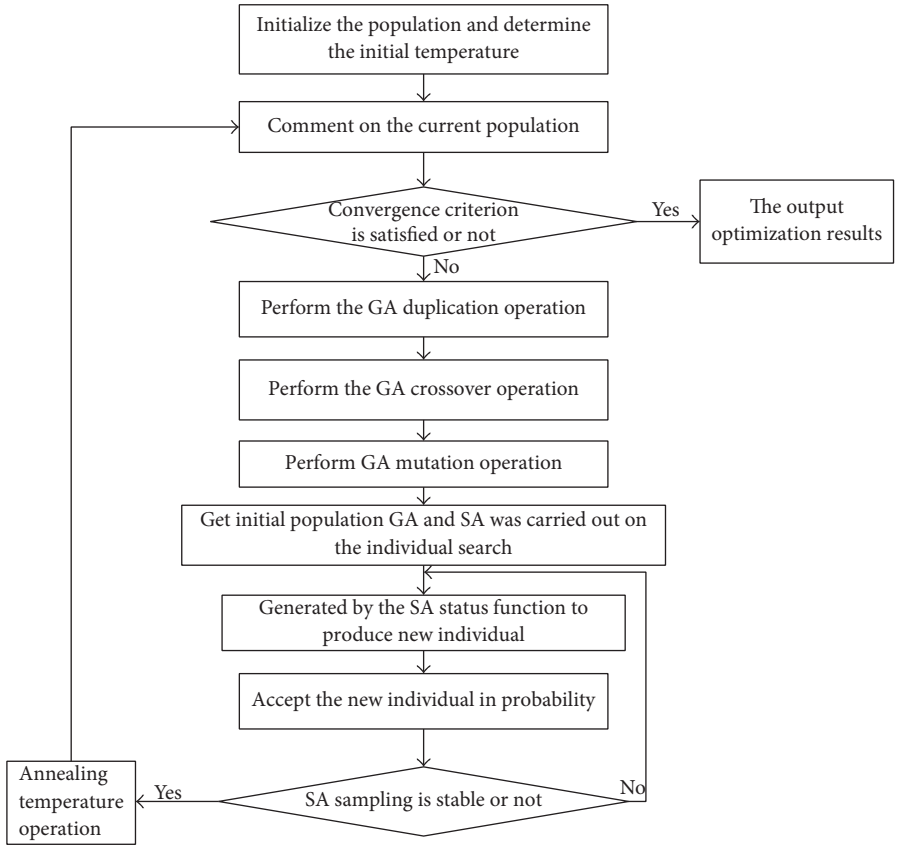

Figure 1: The solving steps of genetic simulated annealing algorithm.

and the stochastic programming constraint (14)

$$\Pr\left[T^l_{M_jP_k}{}' + T^l_{M_jP_k}{}'' + \frac{E\left(R_{M_jP_k}\right)}{V} \le T^l_{M_jP_k}\right] = \beta \tag{19}$$

can be transformed into

$$\begin{aligned}&\mu\left(T^l_{M_jP_k}{}'\right) + \phi^{-1}(\beta)\,\sigma\left(T^l_{M_jP_k}{}'\right) + \mu\left(T^l_{M_jP_k}{}''\right)\\ &\quad + \phi^{-1}(\beta)\,\sigma\left(T^l_{M_jP_k}{}''\right) + \mu\left(\frac{E\left(R_{M_jP_k}\right)}{V}\right)\\ &\quad + \phi^{-1}(\beta)\,\sigma\left(\frac{E\left(R_{M_jP_k}\right)}{V}\right) \le T^l_{M_jP_k}.\end{aligned} \tag{20}$$

3.2. The Solving Thought of Genetic Simulated Annealing Algorithm. The basic idea of genetic simulated annealing algorithm is as follows: firstly encoding the upper planning variables and solving the lower programming to calculate the fitness of each string. And then one can get the best series through copy, crossover, mutation, and simulated annealing. Specific steps are shown as Figure 1.

Step 1. Initialization

(1-1) Set parameters, including the crossover probability of genetic algorithm P_c, mutation probability P_m, each generation population of individuals (chromosomes) number N, and largest evolution algebra Maxgen. Set the evolution algebra gen = 0

(1-2) Confirm the number of inner loops M and the initial value of the temperature T_o of simulated annealing algorithm; let $T = T_o$

(1-3) Determine a reasonable fitness function according to the objective function F_1 of upper programming, determine the encoding way of the decision variable u of upper programming, and randomly generate initial population $X(1) = (\ldots, x_i(1), \ldots)$, $i = 1, 2, \ldots, N$; let gen = 1

Step 2. Take X(gen) into lower programming to be UE distribution calculation, and calculate the fitness of each individual x_i(gen) ($i = 1, 2, \ldots, N$). If gen = Maxgen, the largest fitness chromosome is the optimal solution of resource allocation; else, turn to Step 3.

Step 3. Copy group X(gen) according to the fitness distribution.

Step 4. It is crossover operation according to the crossover probability P_c.

Step 5. Perform mutation operation according to the mutation probability P_m; let gen = gen + 1, get a new population $X(\text{gen})$, and then calculate the fitness of individuals of $X(\text{gen})$.

Step 6. For $i = 1$, conducting the simulated annealing of species $X(\text{gen})$ is as follows:

(6-1) If $i = N$, turn to Step 7; otherwise the cycle counting round $k = 1$, and turn to (6-2).

(6-2) Get individual $x_i(\text{gen})$ by state function, then decode new individuals, and conduct UE distribution calculation under lower programming to get the objective function value of the upper programming, and calculate the fitness.

(6-3) Accept new individual under Metropolis probability acceptance formula.

(6-4) if $k = M$, $i = i + 1$, turn to (6-1); else, $k = k + 1$, turn to (6-2).

Step 7. Annealing temperature: let $T = 0.5T$, and turn to Step 2.

Description is as follows:

(1) The upper decision variables generally take binary encoding; multivariate encoding is as follows:

$$\begin{array}{rcccc} \text{decision variables } u = u_1 & u_2 & \cdots & u_n \\ \text{mapping} \quad \downarrow & \downarrow & \downarrow & \downarrow \\ \text{Chromosome (string) } x = 0011 & 1011 & \ldots & 0110. \end{array} \tag{21}$$

(2) In (1-3), the relationship between the length of the substring β and the precision of decision variables π is

$$\beta \geq \log_2 \left(\frac{u_{\max} - u_{\min}}{\pi} + 1 \right). \tag{22}$$

(3) In a (6-2), SA state function can do random exchange of two different genes positions of chromosome and reverse genes order of different random position of chromosome, such as

$$\begin{array}{rcc} \text{Decision variables } u = & u_1 & u_2 \\ \text{Genes Position} & 2 \;\; 5 & 3 \;\; 7 \\ \text{Chromosome } x = & 01100101 & 10110101. \end{array} \tag{23}$$

Assume that the random variable, respectively, positions are 2 and 3 and 5 and 7, and the new individuals after exchanging and reversing are

$$\begin{array}{l} x_1 = 00101101 \mid 10010111 \\ x_2 = 00011101 \mid 10010111. \end{array} \tag{24}$$

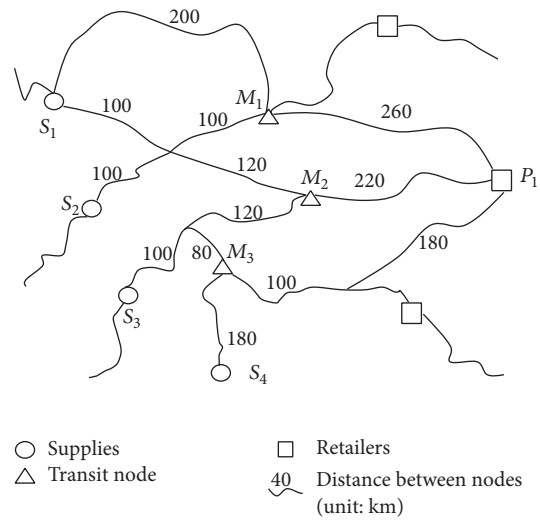

Figure 2: Production and sale collaborative logistics network of one sneaker brand.

Table 1: The distance between each supplier and transit warehouse.

	M_1/km	M_2/km	M_3/km
S_1	200	240	∞
S_2	240	220	∞
S_3	∞	220	180
S_4	∞	∞	180

4. The Sample Simulation

4.1. Sample. Taking the collaborative logistics network production-sales of one sneaker brand as an example, a product retailer put forward a demand of 4000 pieces of goods to the transit warehouse according to the sales plan and product orders. Assume that we can choose goods from four suppliers and three transit warehouses that are available, vehicle average speed is 40 kilometers per hour between various logistics nodes in the process of transportation, the biggest load capacities from suppliers to the transit warehouses and from transit warehouses to retailers are, respectively, 2000 and 3000, and specific arrangement is shown in Figure 2.

The distance between all suppliers to the transit warehouse is shown in Table 1; the suppliers' storage and processing fees for each unit are shown in Table 2. The distance between each transit warehouse to the retailer and the transit warehouses' storage and processing fees for each unit are shown in Table 3.

4.2. Solving Example. The actual, material delivery time that warehouse transit node and retailer require is 10 hours and 12 hours, because of that the supplier and warehouse transit point have some uncertain factors such as the order processing and production, time obeys the normal distribution as Table 4 shows, there are also uncertainty factors on transport which obey the normal distribution table as shown in Table 5, value interval is $\mu \pm 3\sigma$, namely, the probability that the value points fall in the interval is 99.73%, and the probability

Table 2: The material charge and cost for each unit of storage and transportation of suppliers.

	Material charges (RMB)	Storage charges (RMB)	Processing charges (RMB)	Transportation charges (RMB)
S_1	110	0.1	0.15	0.02
S_2	100	0.15	0.15	0.03
S_3	110	0.1	0.1	0.035
S_4	100	0.15	0.1	0.025

Table 3: The distance between retailer and transit warehouses and transit warehouses' cost for unit of storage and transportation.

	Distance (km)	Storage charges (RMB)	Processing charges (RMB)	Transportation charges (RMB)
M_1	260	0.2	0.25	0.02
M_2	220	0.3	0.2	0.025
M_3	280	0.2	0.15	0.015

Table 4: The uncertain index value of the supplier and warehouse transfer point's order processing and production (unit: hours).

	Order processing time	Production and processing time
Supplier	$N(0.1, 5)$	$N(1, 5)$
Storage and transit point	$N(0.2, 5)$	$N(0.5, 5)$

Table 5: The uncertain index value of transport time range of suppliers to transit warehouse and warehouse transfer to seller (unit: hours).

	M_1	M_2	M_3
S_1	$N(5, 5)$	$N(6, 5)$	∞
S_2	$N(6, 5)$	$N(5.5, 5)$	∞
S_3	∞	$N(5.5, 5)$	$N(4.5, 5)$
S_4	∞	∞	$N(4.5, 5)$
Seller	$N(6.5, 5)$	$N(5.5, 5)$	$N(7, 5)$

that ensures finishing the logistics tasks in the time of the warehouse transit node and retailer is 90%, which means α and β both are 90%.

The parameters of the algorithm are as follows: the population size is 50, the crossover probability is 0.6, the probability of mutation is 0.1, the cooling coefficient is 0.95, and the initial temperature is 100. The result converges to the optimal solution after 45 generations by using Matlab7.0 for many times while traditional genetic algorithm iteration number is 64, as shown in Figure 3. The optimal solution in the genetic simulated annealing algorithm is shown in Table 5.

It can be seen as shown in Table 6 that supplier S_1 deployed 1000 unit materials to transit warehouse M_1, supplier S_4, respectively, deployed 1999.99 and 1000.01 unit materials to M_2 and M_3, on the basis of meeting the expected

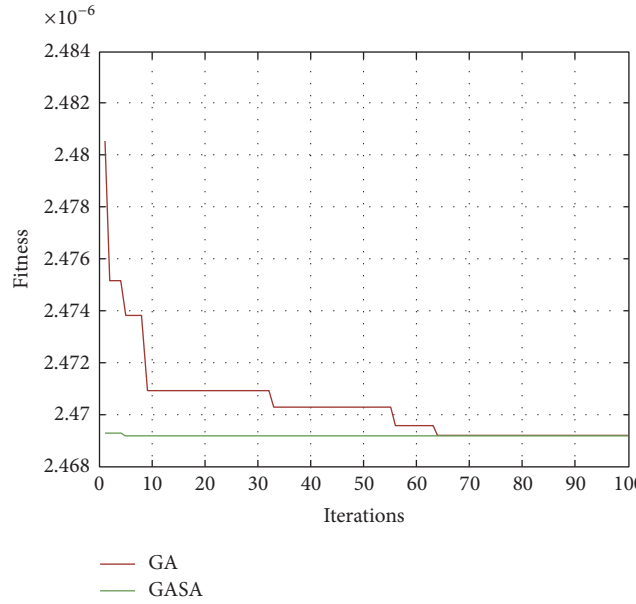

Figure 3: The convergence comparison chart of genetic simulated annealing algorithm and genetic algorithm.

Table 6: The resources allocation for each supplier to the warehouse transfer point.

	M_1	M_2	M_3
S_1	1000		
S_2			
S_3			
S_4		1999.99	1000.01

delivery time, and it makes the supplier's profit maximum 405000 Yuan while retailer's cost is minimum about 19300 Yuan while, on the basis of traditional genetic algorithm, the maximum profit of suppliers is 404990 Yuan. The result indicates that the solution can maximize the interests of both sides, which verify the operability and optimization of the model.

5. Conclusion

Collaborative logistics network is a virtual organization, which is led by manufacturing/service companies or independent third-party logistics enterprise. It is a supply and demand network made up of supply collaboration nodes, function of logistics nodes, and the link road and relationship between nodes; the core task is overall plan and deployment access of the network node resources to realize the overall interests and meet the customer service. Therefore, this paper establishes a supply-sales network on the basis of collaborative logistics network resource allocation model, which includes collaborative logistics network suppliers, warehouse transit nodes, retailers, and their node link. From retailer's demand as a starting point, considering the shipping time and quantity and distribution cost factors, we establish a bilevel programming model with uncertainty factors. On this basis,

we use the genetic simulated annealing algorithm to analyze and solve the model, which can get the optimal scheme that can not only meet suppliers benefit maximization but also make cost minimum to retailers. The analysis results show the feasibility and validity of the model, which can provide the optimal resource allocation decisions and plans.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Risk Analysis on Leakage Failure of Natural Gas Pipelines by Fuzzy Bayesian Network with a Bow-Tie Model

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Pipeline is the major mode of natural gas transportation. Leakage of natural gas pipelines may cause explosions and fires, resulting in casualties, environmental damage, and material loss. Efficient risk analysis is of great significance for preventing and mitigating such potential accidents. The objective of this study is to present a practical risk assessment method based on Bow-tie model and Bayesian network for risk analysis of natural gas pipeline leakage. Firstly, identify the potential risk factors and consequences of the failure. Then construct the Bow-tie model, use the quantitative analysis of Bayesian network to find the weak links in the system, and make a prediction of the control measures to reduce the rate of the accident. In order to deal with the uncertainty existing in the determination of the probability of basic events, fuzzy logic method is used. Results of a case study show that the most likely causes of natural gas pipeline leakage occurrence are parties ignore signage, implicit signage, overload, and design defect of auxiliaries. Once the leakage occurs, it is most likely to result in fire and explosion. Corresponding measures taken on time will reduce the disaster degree of accidents to the least extent.

1. Introduction

Energy is the base of modern industry and the driving force of sustainable development for socioeconomic. In recent years, the energy consumption of natural gas increases rapidly, which results in significantly growth in natural gas industry, such as natural gas reserves, production, and trade volumes. Along with the maturity of the natural gas consuming market, pipeline transportation as a major mode of transport, is rapidly gaining momentum.

But due to the features of the long distance gas pipeline such as high energy and pressure, flammable, toxic, and hazardous characteristics, rupture accidents are likely to occur because of corrosion, material defects, operational errors, or other reasons [1]. In recent years, safety accidents of gas pipelines occur frequently, which caused great casualties and property losses. Systemic and thorough risk analysis may effectively prevent the occurrence of accidents and reduce the losses of accidents to an acceptable level.

At present, lots of qualitative and quantitative risk analysis methods are used for risk assessment of natural gas pipeline leakage, such as the probability and statistics method, analytic hierarchy process [2, 3], Petri nets [4], operability study (HAZOP), fault tree analysis (FTA), event tree analysis (ETA), Bow-tie model, and Bayesian network. These methods can be grossly divided into two groups.

(1) Research based on the probability and statistics method [5–7]: From statistical analysis of typical oil-gas pipeline accidents in the data base, the main factors result in natural gas pipeline leakage failure and accident consequences can be obtained. The leakage failure of natural gas pipelines may occur due to internal and external factors. External factors include corrosion and interference from the third party and natural disaster, while internal factors include material defect, weld-seam defect, and auxiliaries failure.

(2) Construct the risk evaluation framework based on the theory of safety system engineering. FTA, ETA, and Bow-tie model are three typical techniques of this kind.

The fault tree analysis method chooses accidents as the top event. The purpose is to find the direct and indirect causes of top events from top to bottom layers. Yuhua and Datao applied fault tree analysis for oil and gas pipeline leakage [8]. Lavasani et al. enhanced a fuzzy approach to calculate the fuzzy probabilities of the basic events in the fault tree of pipeline failure [9].

Event tree analysis is to consider all aspects of success and failure events according to the accident. Through the event tree analysis method, we can analyze the potential consequences of the accident that may occur in the complex system. Zamalieva et al. proposed a probabilistic model for online scenario labeling in dynamic event tree generation [10]. Brito and de Almeida constructed the event tree of natural gas pipelines [11].

But with only the fault tree and event tree analysis method, the whole process of the accident cannot be described intuitively. Bow-tie method is induced by combining the fault tree and event tree analysis method. With this method, the whole process of the incident is displayed, including causes of the accident, the accident occurrence, prevention, control, and consequences. The traditional Bow-tie analysis method only uses the diagram to describe the process of the accident and do some relevant qualitative analysis. Recent years more accurate quantitative analysis methods with Bow-tie model are studied by researchers. Shahriar et al. constructed a Bow-tie model to analyze oil and gas pipelines risk and employed fuzzy logic to derive fuzzy probabilities of basic events in FTA to estimate fuzzy probabilities of output event consequences [12].

However, fault tree analysis, event tree analysis, and Bow-tie model are methods based on the theory of cut sets, which only conduct the analysis of the two states of events, without reverse inference. Compared to the Bow-tie method, fault tree, and event tree method, Bayesian network carries out two-way analysis, not only to find the results from the causes, but also to find causes from the results. Khakzad et al. combined Bayesian network with fault tree analysis and Bow-tie model for risk analysis for safety analysis in process facilities and offshore drilling operations, respectively [13, 14]. Li et al. analyzed the leakage failure risk of submarine oil and gas pipelines by Bayesian network with Bow-tie model [15].

The purpose of this study is to develop an effective approach for the risk analysis of natural gas pipelines. A risk assessment method based on Bow-tie model and Bayesian network is proposed in this paper. The Bow-tie diagram of the natural gas pipeline leakage is constructed based on the potential risk factors and consequences of the failure. Bayesian networks converted from the Bow-tie model are conducted to analyze the risk of natural gas leakage. The probability of the failure and corresponding consequences are obtained through Bayesian inference as the weak links between the failure and the risk factors in the system. Pipelines are easily influenced by the external environment and internal factors. Differences even exists in pipelines located in the same area at different time, in terms of geological soil conditions, material property, running state, and corrosion protection measures. It indicates that factors which affect the running of natural gas pipelines are of great uncertainty and vagueness. In order to deal with this problem, a fuzzy logic method is proposed to determine the prior probability of basic events.

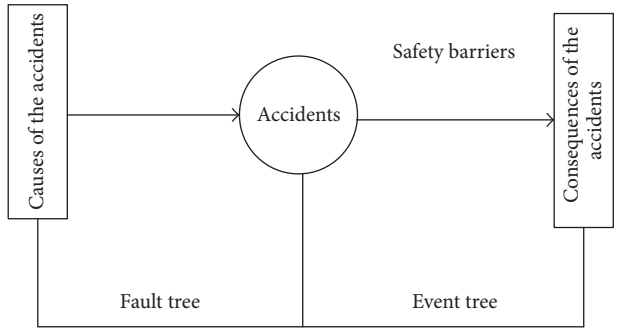

Figure 1: Bow-tie model structure model.

The paper is organized as follows. After the introduction, the basic concepts of Bow-tie model and Bayesian network are introduced in Section 2. The proposed framework of risk analysis based on Fuzzy Bayesian network with Bow-tie model is presented in Section 3. A practical case is studied by using the proposed method in Section 4. Finally, conclusions and future work are discussed in Section 5.

2. Risk Analysis Techniques

2.1. Bow-Tie Model. Bow-tie analysis was proposed by University of Queensland in Australia in 1979. Due to the characteristics of intuition, simplicity, and visibility, it has been widely used in the safety management areas. A Bow-tie model is a combination of a fault tree and an event tree. Accident hazard source, critical event, safety barriers, and the consequences of the failure are the chief components of a Bow-tie model. Accident hazard source refers to the risk factors of the failure. Critical event is the failure itself and safety barriers are measures taken to reduce the losses of the failure. The structure of the Bow-tie model is shown in Figure 1.

As seen from Figure 1, the construction of a Bow-tie model of an accident is a two-step process. The first step is fault tree analysis, which is the left part of the Bow-tie model. It is comprised of identifying the risk factors of the system to be evaluated and choosing the critical event that is most likely to occur as the top event. The second step is event tree analysis, which is the right part of the Bow-tie model. It starts from the critical event and follows with the possible consequences after a series of failure prevention and mitigation measures.

Bow-tie model takes advantages of the fault tree analysis and the event tree analysis. Not only can the cause of the accident be found, but also the consequences of the accident can be displayed, which is convenient for the following research on risk assessment.

2.2. Bayesian Network. Bayesian network, also known as Bayesian reliability network, is a probabilistic technique based on graph theory and probability theory. In a Bayesian network, each node represents an information element.

The directed edge between nodes indicates the degree of association between the information elements. Through a directed acyclic graph, the relationship and the influence extent between various elements of a network structure can be represented intuitively. In Bayesian networks, nodes without any incoming arrow are called root nodes, which have a priori probability distribution. Other nodes are called leaf nodes. Nodes the arrow points to are called the child nodes, and the source nodes of the arrow are called the parent nodes. Each child node has a conditional probability distribution (or function) in condition of the parent nodes.

P is conditional probability distribution. $B(A_i)$ and $A(A_i)$ are the parent node set and nondescendant node set of A_i, respectively. For nodes without an edge, they are independent. That is to say, under the given condition of $B(A_i)$, A_i and $A(A_i)$ are conditional independence. So

$$P\left(A_i \mid \left(B\left(A_i\right), A\left(A_i\right)\right)\right) = P\left(A_i \mid B\left(A_i\right)\right). \tag{1}$$

The conditional probability $P(A_i \mid B(A_i))$ expresses the connection between the node A_i and their parent nodes $B(A_i)$. Once the prior probability distribution of the root node and the conditional probability distribution of the nonroot nodes is given, joint probability distribution is

$$\begin{aligned} P(A) &= P\left(A_1, A_2, \ldots, A_n\right) \\ &= \prod_{i=1}^{n} P\left(A_i \mid B\left(A_1, A_2, \ldots, A_{i-1}\right)\right). \end{aligned} \tag{2}$$

According to the principle of the Bayesian network, forward prediction and backward diagnosis can be carried out as follows.

(1) Forward prediction is prediction of the probability of the failure and potential consequences based on the causes events' probability. The prior probability of the cause event A_i is $P(A_i)$, the probability of the consequence event R is $P(R)$, and the conditional probability of consequence event R in condition of the cause event A_i is $P(R \mid A_i)$. Then,

$$P(R) = \sum_{i=1}^{n} P\left(A_i\right) P\left(R \mid A_i\right). \tag{3}$$

(2) Backward diagnosis is to infer the causes events' probability from the already happened consequence events' probability. Then diagnose the cause of the event (accident, failure, and pathology) according to the probability. The prior probability of cause event A_i is $P(A_i)$, and the conditional probability of the cause event A_i in condition of the consequence event R is $P(A_i \mid R)$; then

$$P\left(A_i \mid R\right) = \frac{P\left(R \mid A_i\right) P\left(A_i\right)}{\sum_{i=1}^{n} P\left(R \mid A_i\right) P\left(A_i\right)}. \tag{4}$$

3. Framework of Risk Analysis Based on Fuzzy Bayesian Network with a Bow-Tie Model

3.1. Collect Necessary Information of the Risk. In order to deeply analyze the causes and consequences of the occurrences, it is of great importance to comprehensively understand the normal operation conditions, the failure consequences, and preventive measures by collecting the history data, consulting professionals, and reviewing literatures.

3.2. Analysis of the Cause Factors of the Failure and Construction of the Fault Tree. The cause factors can be studied in several ways, such as man-made factors and nonhuman factors, internal factors and external factors, or different types leading to the failure. Find the deep reasons layer by layer gradually until the bottom event. Then construct the fault tree, which chooses the failure as the top event, and build a relationship between the direct cause, the indirect cause, and the top event. Then qualitative and quantitative analyses are carried according to the fault tree.

3.3. Analysis of Consequences and Construction of the Event Tree. Event tree analysis method starts with the failure and develops with success or failure events caused by the accident and measures adopted in chronological order. Then qualitative and quantitative analysis of consequences in the system are carried out according to the event tree.

3.4. Construction of the Bow-Tie Model. The fault tree, a dendrogram with basic events, intermediate events, and top events connected by the logic gates and transfer symbols, is located on the left of the Bow-tie model. On the right side of the Bow-tie model is the event tree, which starts with a primary event and develops in accordance with the subsequent measures taken successfully or not until the final consequences. The Bow-tie method can be used in both qualitative analysis and quantitative calculation.

3.5. Convert the Bow-Tie Diagram into the Bayesian Network. According to the logic relationship and connection strength of events involved in the Bow-tie diagram, the mapping relation of the Bow-tie model and a Bayesian network is constructed. Bayesian network is composed of 1 directed acyclic graph and lots of corresponding conditional probability tables.

In the process of mapping from Bow-tie model to a Bayesian network, nodes in the Bayesian network correspond to events one by one in the Bow-tie diagram. For repeating events, only one node is established. For basic events and consequence events, the prior distribution of the root node in the Bayesian network is determined according to the probability. Conditioned probabilities of the intermediate nodes are obtained by the joint conditions between nodes.

3.6. Bayesian Network Prediction and Diagnosis

3.6.1. Determine the Prior Probabilities of the Root Nodes. Bayesian network is a risk quantification method based on

Bayesian reasoning. In many studies, the prior probability distribution of the basic event is a determined value based on a large number of trials or statistical data from the data manual. However, for cases with insufficient statistical data and knowledge, the failure rates of events are of great uncertainty. In this paper, we use fuzzy linguistic probabilities instead. The probability of the event is defined by a fuzzy number from the experts' elicitation. The detailed computational process is described as follows.

A group of M experts with different professional position, service time, and education level are selected for evaluating the probability of events. For the kth expert, the judgement of the likelihood for the occurrence of the ith events is described by a linguistic variable, which corresponds to a trapezoidal fuzzy number $E_{ki} = (t_1, t_2, t_3, t_4)$.

The membership function of the trapezoidal fuzzy number $E_{ki} = (t_1, t_2, t_3, t_4)$ is defined as

$$u_L(x) = \begin{cases} 0 & x \le t_1 \\ \dfrac{x - t_1}{t_2 - t_1} & t_1 < x \le t_2 \\ 1 & t_2 < x \le t_3 \\ \dfrac{t_4 - x}{t_4 - t_3} & t_3 < x \le t_4 \\ 0 & t_4 < x \end{cases}. \tag{5}$$

Similarity aggregation method (SAM) is employed for aggregating experts' judgement [9]. The weighting criteria of the experts are shown in Table 1.

Steps of SAM are described as follows.

(I) Calculate the Degree of Agreement between Expert m and Expert n. $E_m = (a_1, a_2, a_3, a_4)$ and $E_n = (b_1, b_2, b_3, b_4)$ are standard trapezoidal fuzzy numbers corresponding to the judgements of expert m and expert n. The agreement function of expert m and expert n is defined as

$$S_{mn} = 1 - \frac{1}{4}\sum_{i=1}^{4} |a_i - b_i| \tag{6}$$

which denotes the degree of similarity between the experts.

(II) Calculate Experts' Average Agreement (AA) Degree. The Average Agreement (AA) degree is defined as

$$\mathrm{AA}_m = \frac{1}{M-1}\sum_{\substack{n=1 \\ n \ne m}}^{M} S_{mn}. \tag{7}$$

(III) Calculate the Experts' Relative Agreement (RA) Degree. The Relative Agreement (RA) degree is defined as

$$\mathrm{RA}_m = \frac{\mathrm{AA}_m}{\sum_{k=1}^{M} \mathrm{AA}_k}. \tag{8}$$

(IV) Calculate Experts' Consensus Coefficient (CC) Degree. The Consensus Coefficient (CC) degree is defined as

$$\mathrm{CC}_m = \beta \cdot w_m + (1 - \beta)\,\mathrm{RA}_m, \tag{9}$$

where β is a relaxation factor of SAM method and $\beta \in [0, 1]$.

(V) Calculate the Aggregated Result of Experts' Judgments AG. The aggregated result of experts' judgments is defined as

$$E_{\mathrm{AG}} = C_1 \times E_1 + C_2 \times E_2 + \cdots + C_M \times E_M. \tag{10}$$

The center area method, which is a frequently used approach for fuzzy number defuzzification, is employed to convert the trapezoidal fuzzy number $E_{\mathrm{AG}} = (t_1, t_2, t_3, t_4)$ to a crisp number. It is expressed by

$$P^* = \frac{\int_{t_1}^{t_2} ((x - t_1)/(t_2 - t_1))\, x\, dx + \int_{t_2}^{t_3} x\, dx + \int_{t_3}^{t_4} ((t_4 - x)/(t_4 - t_3))\, x\, dx}{\int_{t_1}^{t_2} ((x - t_1)/(t_2 - t_1))\, dx + \int_{t_2}^{t_3} dx + \int_{t_3}^{t_4} ((t_4 - x)/(t_4 - t_3))\, dx} = \frac{1}{3}\frac{(t_4 + t_3)^2 - t_4 t_3 - (t_1 + t_2)^2 + t_1 t_2}{(t_4 + t_3 - t_1 - t_2)}. \tag{11}$$

Finally, the fuzzy probabilities P can be obtained from the fuzzy possibility as

$$P = \begin{cases} \dfrac{1}{10^Z} & P^* \ne 0 \\ 0 & P^* = 0, \end{cases} \tag{12}$$

where

$$Z = 2.301 \left(\frac{1 - P^*}{P^*}\right)^{1/3}. \tag{13}$$

3.6.2. Determine the Conditional Probabilities of the Leaf Nodes. Conditional probabilities of the leaf nodes depend on the logical relationship of events. They can be obtained according to Figures 2 and 3.

3.6.3. Risk Analysis and Prediction Based on Bayesian Network. Based on the constructed topology network structure and the state values of nodes, forward prediction and backward diagnosis can be carried out using the Bayesian network inference. Through the forward prediction we can predict the consequences probability, while by the backward diagnosis we can get the critical causes of the failure and estimate the posterior probability of the basic events.

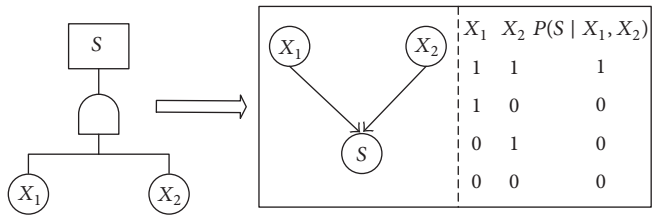

Figure 2: And gate.

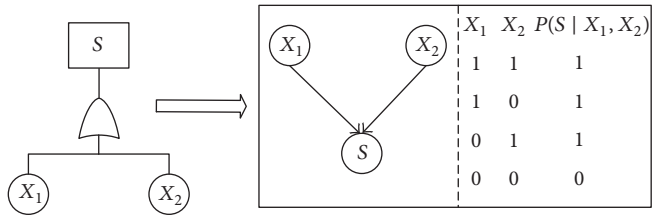

Figure 3: Or gate.

Table 1: Weighting criteria of a group of experts.

	Constitution	Score
Professional position	Senior academic	8
	Junior academic	6
	Engineer	4
	Technician	2
	Worker	1
Service time	≥20 years	8
	15–20	6
	10–15	4
	5–10	2
	≤5	1
Education level	PhD	8
	Master	6
	Bachelor	4
	HND	2
	School level	1

4. Risk Analysis of Natural Gas Pipeline Failure Based on Fuzzy Bayesian Network with a Bow-Tie Model

4.1. Bow-Tie Model of Natural Gas Pipeline Failure

4.1.1. Analysis of Risk Factors and Constructing the Fault Tree. Failure of natural gas pipelines refers to gas leakage of pipelines due to puncture and rupture, which is the critical event of the Bow-tie model. In order to evaluate the risk of natural gas pipeline failure, risk factors in the natural gas pipeline transportation process should be analyzed at first.

The fault tree is constructed based on a comprehensive analysis of natural gas pipeline failures and standards of gas pipelines design, construction, operation, and maintenance.

Table 2: Description of the basic events.

No.	Description
$X_{4\text{-}1}$	Risk of interference from the third party due to parties ignore signage
$X_{4\text{-}2}$	Risk of interference from the third party due to implicit signage
$X_{4\text{-}3}$	Risk of interference from the third party due to sabotage
$X_{4\text{-}4}$	Risk of interference from the third party due to overload
$X_{5\text{-}1}$	Risk of natural disaster due to earthquake
$X_{5\text{-}2}$	Risk of natural disaster due to flood
$X_{5\text{-}3}$	Risk of natural disaster due to subsidence
$X_{6\text{-}1}$	Risk of material defect due to design defect of material
$X_{6\text{-}2}$	Risk of material defect due to construction defect of material
$X_{7\text{-}1}$	Risk of weld-seam defect due to design defect of weld-seam
$X_{7\text{-}2}$	Risk of weld-seam defect due to construction defect of weld-seam
$X_{8\text{-}1}$	Risk of auxiliaries due to design defect of auxiliaries
$X_{8\text{-}2}$	Risk of auxiliaries due to construction defect of auxiliaries
$X_{9\text{-}1}$	Risk of external corrosion due to failure of CP
$X_{9\text{-}2}$	Risk of external corrosion due to failure of coating
$X_{9\text{-}3}$	Risk of external corrosion due to failure of soil corrosion
$X_{11\text{-}1}$	Risk of internal corrosion due to water medium
$X_{11\text{-}2}$	Risk of internal corrosion due to aid medium
$X_{12\text{-}1}$	Risk of internal corrosion due to failure of inhibitor
$X_{12\text{-}2}$	Risk of internal corrosion due to failure of coating
$X_{12\text{-}3}$	Risk of internal corrosion due to debonding

The fault tree is shown in Figure 4 and basic events in the fault tree are listed in Table 2.

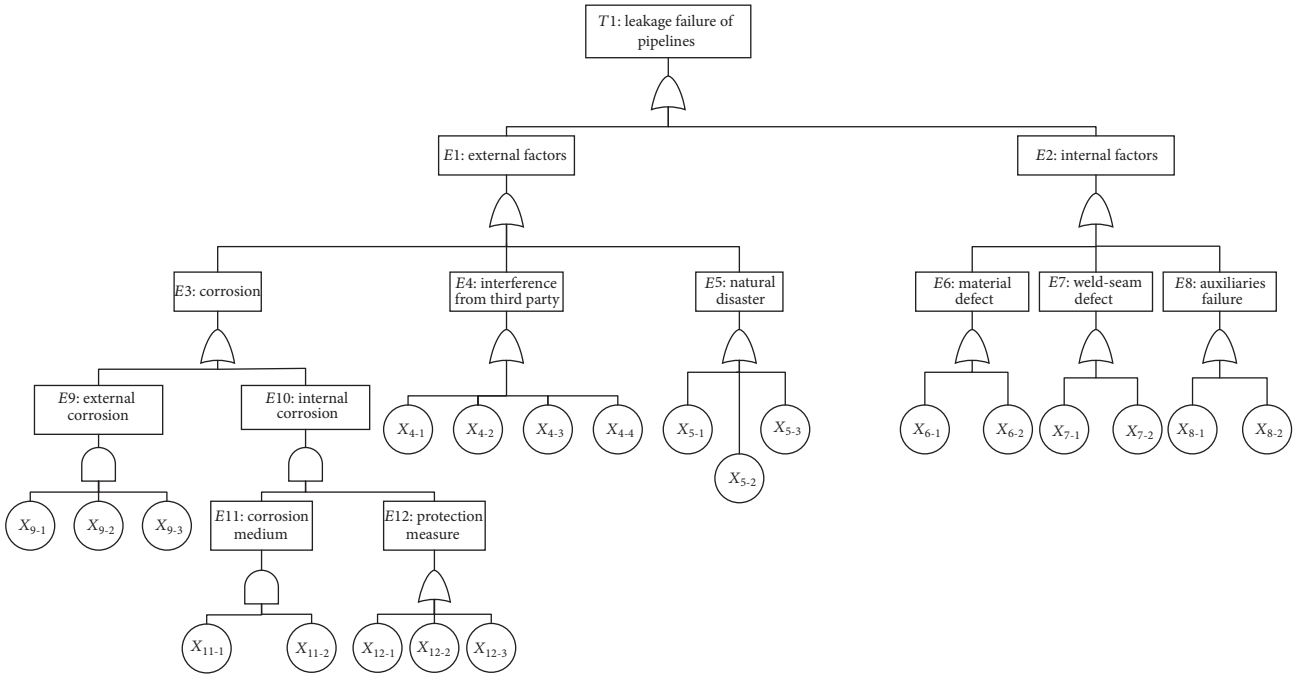

Figure 4: The fault tree of the natural gas leakage.

The fault tree displays the potential factors that may cause pipeline leakage. The leakage failure of natural gas pipeline may occur due to internal and external factors. External factors include corrosion, interference from the third party, and natural disaster, while internal factors include material defect, weld-seam defect, and auxiliaries' failure.

Corrosion may lead to pipeline puncture and rupture, which determine the way and rate of gas leakage. There are two kinds of corrosion, internal corrosion and external corrosion. Internal corrosion is mostly due to corrosive medium and failure of corrosion protection measures. Corrosive medium includes water and aid medium. Corrosion protection measures consist of injection of corrosion inhibitor, anticorrosion coatings fabrication, and pipe cleaning. External corrosion is mainly attributed to the failure of CP, the failure of coating, and soil corrosion.

The interference from third party is also an important risk factor, including parties ignore signage, implicit signage, sabotage, and overload that may cause serious damage to pipeline. Natural disasters including earthquake, flood, and subsidence also cannot be ignored for pipeline leakage.

The material and weld-seam defect are inherent defect caused by incorrect design or error operation factor during the design and construction stages. Once there are external forces, these defects may lead to pipeline leakage. Besides, failure of pipeline auxiliaries such as flange, valve, due to design fault, or aging may also lead to a leakage occurrence or situations out of control.

4.1.2. Event Tree Analysis. The main component of natural gas is methane, with a small amount of ethane, propane, and sulfur gases. And the characteristics of natural gas pipeline leakage are different from other transport modes of dangerous chemicals.

The consequences of the natural gas leakage are serious. Natural gas is highly flammable and explosive. There will be an explosion if the leakage concentration reaches 5%. So the space confinement is the critical factor which determines what kind of disaster will happen.

Once the natural gas leakage occurs, gas will spread with wind, which will result in a wide range of casualties. Gas lighter than air especially will diffuse in the air. It easily forms an explosive mixture with air and explodes wherever there is a fire source. Gas heavier than air will gather in the ground, ditches, and blind corner, with accumulation for a long time. Once it catches fire, there will be an explosion with serious air pollution.

The graphical environment of areas along the pipeline is much complicated, sometimes with a large population. Fire, explosion, or other accidents due to natural gas leakage will cause enormous losses and threat to the property and safety of the lives of the people.

The potential consequences of natural gas pipeline leakage may be detonation or deflagration, fireball or jet fire, confined vapor cloud explosion, flash fire, with casualties, poisonousness, contamination and material loss of different degree. Safety barrier such as ignition and evacuation should be carried out in order to reduce the loss of the gas pipeline leakage. In the event tree, select the leakage of natural gas as the primary event. We can get all of the consequence of the accident, which is shown in Figure 5. The detailed descriptions of the consequences are listed in Table 3.

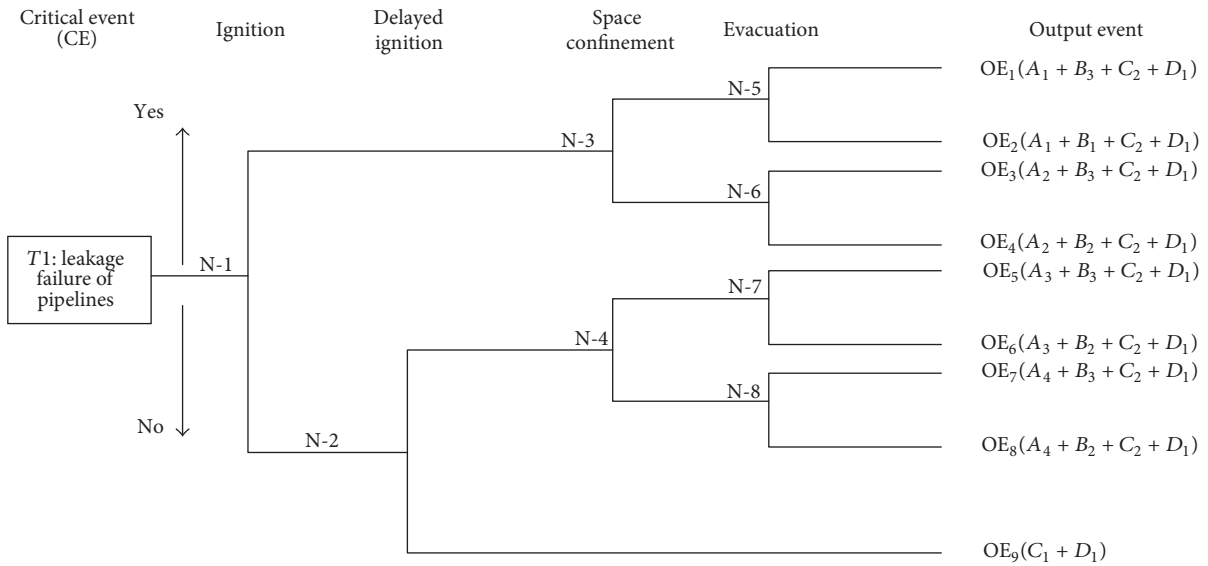

Figure 5: The event tree of the natural gas leakage.

Table 3: Consequence of the event tree.

No.	Consequence
A_1	Detonation or deflagration
A_2	Fireball or jet fire
A_3	Confined vapor cloud explosion
A_4	Flash fire
B_1	Severe casualties
B_2	Light casualties
B_3	No casualties
C_1	Severe poisoning and contamination
C_2	Light poisoning and contamination
D_1	Material loss

4.1.3. Bow-Tie Model Construction. With the fault tree on the left and the event tree on the right, Bow-tie model of natural gas pipeline leakage is shown in Figure 6.

4.2. Bayesian Network for Natural Gas Pipeline Failures. According to the events, the logic gate, and the connection strength involved in the Bow-tie diagram, we established the main mapping relation of the Bayesian network, according to which the Bow-tie diagram is converted to a Bayesian network. The Bayesian Network for natural gas pipeline failures is shown in Figure 7.

4.3. Statistical Analysis

4.3.1. Calculate the Failure Probability of the Basic Events. Lack of data and uncertainty in the risk assessment process is a major problem in the natural gas pipeline risk analysis. Here experts' judgements are used to evaluate the failure probability of the basic events, in terms of linguistic variables with a number of linguistic terms such as "very high," "high," and "low." To solve the language ambiguity problem, fuzzy sets theory is employed to convert the linguistic term to a fuzzy number. While the number of the linguistic terms of a linguistic variable increases, the accuracy of the model increases but so does the numerical complexity. In order to balance the accuracy and complexity of the model, 5-granular scale is chosen in this analysis. Experts make a judgement for the failure probability of each event with linguistic terms such as very low, low, medium, high, and very high. Each linguistic term is defined as a trapezoidal fuzzy number in Table 4.

Table 4: Fuzzy scales.

Linguistic terms	Scale
Very low	(0, 0, 0.1, 0.2)
Low	(0.1, 0.25, 0.4)
Medium	(0.3, 0.5, 0.7)
High	(0.6, 0.75, 0.9)
Very high	(0.8, 0.9, 1, 1)

Four experts from related areas of natural gas pipeline transportation industry are employed for evaluating the failure probability of events with uncertainty and lack of sufficient data. Profession position, education level, and service time are considered in the expert selected process to reflect the actual situation objectively. The weighting criteria of experts are shown in Table 5.

The weight coefficients of experts are changed along with their different backgrounds and experts' scores. Experts' judgements are aggregated by the SAM technique discussed in Section 3. The defuzzified possibilities are obtained by (11). Equations (12) and (13) are employed to get the probabilities. Detailed results are shown in Table 6.

Conditional probabilities depend on the logical relationship of events. They can be obtained according to Figures 2 and 3.

Based on the constructed topology network structure and the state values of nodes, the probability updating is

Table 5: Weighting criteria of four experts.

Expert	Professional position	Service time	Education level	Weighting score
Expert 1	Senior academic	≥20 years	PhD	0.32
Expert 2	Junior academic	15–20	PhD	0.3
Expert 3	Engineer	5–10	PhD	0.21
Expert 4	Junior academic	15–20	Bachelor	0.17

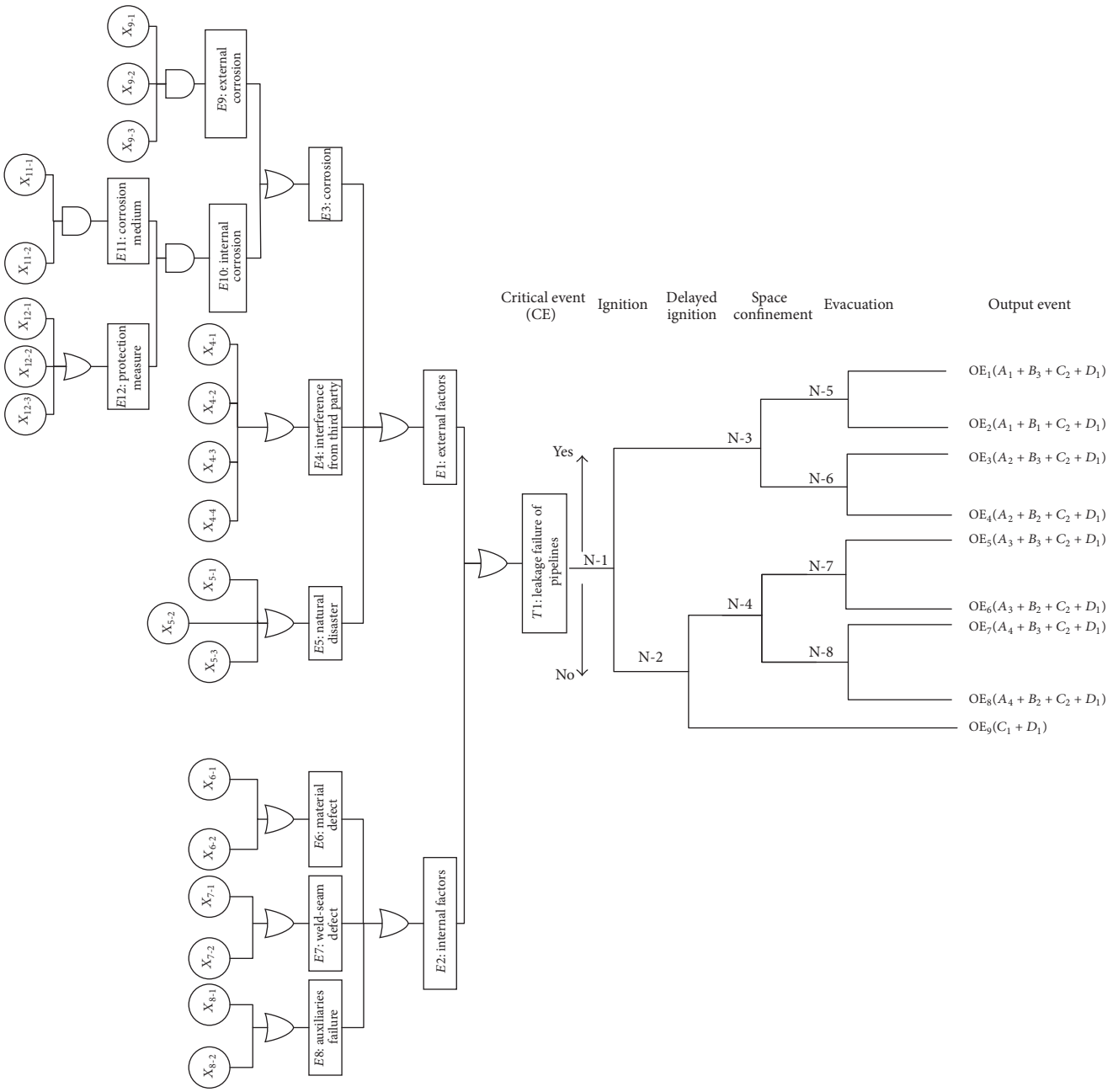

Figure 6: The Bow-tie model of natural gas leakage.

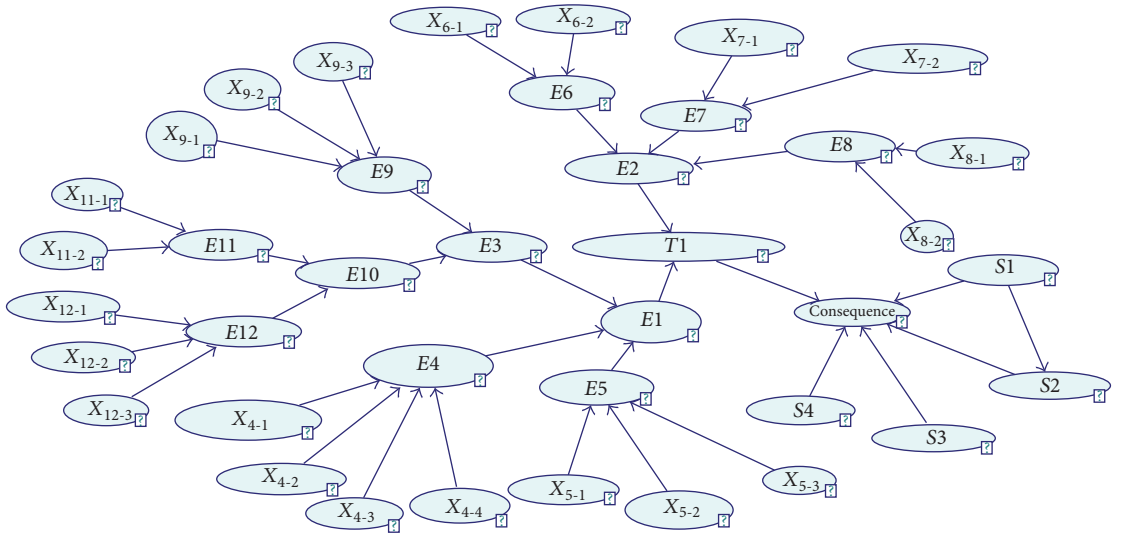

Figure 7: The Bayesian network of natural gas leakage.

Table 6: Prior probabilities of basic events based on SAM.

Basic event	Linguistic expressions	Aggregated expert decision				Defuzzed possibility	Prior probability
X_{4-1}	(m, m, m, l)	0.2619	0.4524	0.4524	0.6429	0.4524	0.0035
X_{4-2}	(m, m, l, l)	0.2121	0.3902	0.3902	0.5682	0.3902	0.0021
X_{4-3}	(l, m, m, l)	0.2015	0.3769	0.3769	0.5523	0.3769	0.0019
X_{4-4}	(l, vl, vl, vl)	0.0272	0.0680	0.1408	0.2544	$1.26E-01$	$4.06E-05$
X_{5-1}	(vl, vl, vl, vl)	0	0	0.1000	0.2000	$7.78E-02$	$5.66E-06$
X_{5-2}	(vl, l, l, vl)	0.0508	0.1269	0.1761	0.3015	$1.67E-01$	$1.16E-04$
X_{5-3}	(l, l, vl, vl)	0.0561	0.1402	0.1841	0.3121	$1.76E-01$	$1.41E-04$
X_{6-1}	(vl, vl, l, l)	0.0439	0.1098	0.1659	0.2879	$1.55E-01$	$8.88E-05$
X_{6-2}	(l, l, l, l)	0.1000	0.2500	0.2500	0.4000	$2.50E-01$	$4.80E-04$
X_{7-1}	(l, vl, l, l)	0.0735	0.1839	0.2103	0.3471	$2.06E-01$	$2.45E-04$
X_{7-2}	(l, l, vl, l)	0.0781	0.1952	0.2171	0.3562	$2.13E-01$	$2.78E-04$
X_{8-1}	(vl, vl, vl, l)	0.0196	0.0491	0.1295	0.2393	$1.13E-01$	$2.62E-05$
X_{8-2}	(m, m, h, l)	0.3263	0.5057	0.5057	0.6851	0.5057	0.0052
X_{9-1}	(l, l, vl, l)	0.0781	0.1952	0.2171	0.3562	$2.13E-01$	$2.78E-04$
X_{9-2}	(l, l, vl, l)	0.0804	0.2009	0.2205	0.3607	$2.17E-01$	$2.96E-04$
X_{9-3}	(h, m, h, m)	0.4545	0.6288	0.6288	0.8030	0.6288	0.0117
X_{11-1}	(l, l, l, l)	0.1000	0.2500	0.2500	0.4000	$2.50E-01$	$4.80E-04$
X_{11-2}	(l, l, l, vl)	0.0804	0.2009	0.2205	0.3607	$2.17E-01$	$2.96E-04$
X_{12-1}	(l, l, l, l)	0.1000	0.2500	0.2500	0.4000	0.25	$4.80E-04$
X_{12-2}	(l, l, l, vl)	0.0804	0.2009	0.2205	0.3607	$2.17E-01$	$2.96E-04$
X_{12-3}	(l, l, vl, l)	0.0781	0.1952	0.2171	0.3562	$2.13E-01$	$2.78E-04$

conducted by Bayesian dynamic reasoning and analysis. The failure probability of natural gas pipeline leakage calculated is 0.014, which implies that the pipeline leakage is likely to occur. The occurrence probabilities of consequences are shown in Table 7.

For natural gas pipeline leakage risk analysis, we set leakage failure and OE6 as the evidence to estimate the posterior probability of the basic events. Results are shown in Table 8.

According to Table 8 and Figure 8, for most of the basic events, the posterior probabilities are greater than the prior probabilities. The most likely causes of natural gas pipeline leakage occurrence are parties ignore signage, implicit signage, overload, and design defect of auxiliaries. The most probable accident evolution paths are that (1) material design defect and material construction defect causes the pipeline leakage; (2) weld seam design problem and weld seam construction problem cases leakage

Table 7: Occurrence probabilities of consequences.

Consequences	Occurrence probability
OE0	$9.86E-01$
OE1	$7.36E-03$
OE2	$4.90E-03$
OE3	$8.17E-04$
OE4	$5.45E-04$
OE5	$2.21E-04$
OE6	$1.47E-04$
OE7	$2.45E-05$
OE8	$1.63E-05$
OE9	$1.26E-05$

Table 8: Posterior probabilities of basic events.

Basic event	Prior probability	Posterior probability
$X_{4\text{-}1}$	0.0035	0.2492
$X_{4\text{-}2}$	0.0021	0.1495
$X_{4\text{-}3}$	0.0019	0.0019
$X_{4\text{-}4}$	$4.06E-05$	$1.35E-01$
$X_{5\text{-}1}$	$5.66E-06$	$4.00E-04$
$X_{5\text{-}2}$	$1.16E-04$	$8.30E-03$
$X_{5\text{-}3}$	$1.41E-04$	$1.00E-03$
$X_{6\text{-}1}$	$8.88E-05$	$6.30E-03$
$X_{6\text{-}2}$	$4.80E-04$	$3.42E-03$
$X_{7\text{-}1}$	$2.45E-04$	$1.74E-02$
$X_{7\text{-}2}$	$2.78E-04$	$1.98E-02$
$X_{8\text{-}1}$	$2.62E-05$	$1.70E-03$
$X_{8\text{-}2}$	0.0052	0.3702
$X_{9\text{-}1}$	$2.78E-04$	$2.78E-04$
$X_{9\text{-}2}$	$2.96E-04$	$2.96E-04$
$X_{9\text{-}3}$	0.0117	0.0117
$X_{11\text{-}1}$	$4.80E-04$	$4.80E-04$
$X_{11\text{-}2}$	$2.96E-04$	$2.96E-04$
$X_{12\text{-}1}$	$4.80E-04$	$4.80E-04$
$X_{12\text{-}2}$	$2.96E-04$	$2.96E-04$
$X_{12\text{-}3}$	$2.78E-04$	$2.78E-04$

failure. So it is important to strengthen the prevention of the weak links in order to control the occurrence of the accident.

The analysis also shows that once the natural gas pipeline leakage occurs, if action was not taken timely, natural gas will be mixed with the air and reaches a certain concentration quickly, resulting in fire and explosion. So it is necessary to take action on time to mitigate the consequences of the accident.

5. Conclusions

Leakage of natural gas pipeline may result in serious accidents such as fire, exposition, and combustion with heavy casualties and huge economic losses. A comprehensive and effective risk assessment method is of great significance for risk analysis of

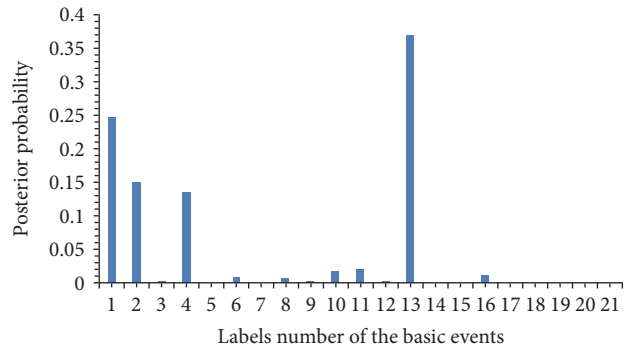

Figure 8: Histogram of the posterior probability of basic events.

natural gas pipelines. Fault tree analysis, event tree analysis, and Bow-tie model are excellent methods for risk analysis. However, they only conduct the analysis from the causes to the results, without reverse inference.

In this paper, a quantitative risk analysis approach for natural gas pipelines is constructed by a Bow-tie model coupled with Bayesian network. After identifying the potential risk factors for leakage of natural gas pipelines and finding the possible consequences of pipeline leakage, a Bow-tie model for risk management of natural gas pipelines is constructed and then converted to a Bayesian network according to a mapping relation. In the Bayesian network, the quantification of the risk factors associated with pipeline leakage depends on the prior probability of the basic events, which are often not reliable, applicable, or available. Fuzzy logic is employed as an approach to solve this problem. The failure probabilities of the basic events are obtained from the fuzzy possibility, which is calculated by converting the experts' linguistic judgement to aggregated results with similarity aggregation method and defuzzification techniques.

Through forward prediction of the Bayesian network, we can get the occurrence probabilities of natural gas pipeline leakage and the consequences. The posterior probabilities of basic events and consequences are determined by backward diagnosis of the Bayesian network, which can be used to find the weak links existing in the natural gas pipelines. The main causes of natural gas pipeline leakage occurrence are design defect of auxiliaries and interference for the third party, especially the parties ignore signage. The corresponding preventive measures will decrease the probability of natural gas leakage. The disaster degree of accidents after natural gas leakage will be reduced to the least extent if mitigation measures are taken on time.

The framework of the proposed method improves the scientific and effective natural gas pipeline management and provides technical support for the implementation of the natural gas pipeline integrity management. However, data presented in this study mainly relies on the expert' judgement. In the future research, historical data and statistic data will be concluded with the approach. The sensitivity analysis should also be discussed.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Noninterest Income and Performance of Commercial Banking in China

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Noninterest income is what most Chinese banks are striving for in recent years because of the vigorous competition among commercial banks due to the increasingly open market and tough regulation from the central bank of China. But the problem is the real effect of noninterest income on profit and risks. A panel threshold model is used with balanced panel dataset of 16 listed Chinese commercial banks, for the period of 2007 to 2013, to investigate the relationship between noninterest income and performance. The findings show two main conclusions: (1) the existence of two thresholds shows that there is nonlinear relationship; (2) there is a general negative correlation between the noninterest income ratio and performance of commercial banks. Furthermore, when the noninterest income ratio is higher than the two thresholds, the negative correlation decreases. Implications of the paper are that the ratio should be controlled in a range or noninterest income will not positively affect the performance, and a high level of performance can be gained only by raising the ratio to a certain level.

1. Introduction

With the significant development of financial liberalization and globalization, banks choosing to expand their noninterest income activities are confronted with increasingly severe interbank competition so as to grow, realize efficiency, and reduce idiosyncratic risk [1]. The Chinese banking industry has just started its focus on diversification of business in recent years. The noninterest income business has had continuous development. But whether noninterest income can help enhance bank performance has always been controversial. Some previous literature pays a lot of attention to the relationship between noninterest based activities and the performance of banks in countries outside of China. However, similar attention has not been given much to the Chinese case. This paper investigates the relationship between noninterest income ratio and the performance of Chinese commercial banks' and the influence of noninterest income ratio on its performance. The remainder of the paper is structured as follows. In Section 2 we describe recent academic developments in this field. In Section 3 we review mechanism of the noninterest income which affects the performance. In Section 4 the dataset and the empirical model are described. In Section 5 we present and interpret the empirical results. Finally, policy implication of the paper has been drawn in Section 6.

2. Literature Review

Researchers from USA, UK, India, Ghana, and so on have explored relationships between noninterest income and business performance [2–11] (Abeyratna Gunasekarage et al., 2014). There are three different schools of thought on optimal bank scope. One set of arguments hold that restricting banking scope to the traditional activities reduces likelihood of failure related to risk businesses, while the second set argue that noninterest income enhances bank profitability and reduces risk; the third set holds that impact of noninterest income on bank performance is uncertain.

Some researchers deem that noninterest income business can improve the total income, since banks can expand the source of income by diversifying income. Eisemann [12] stated that the noninterest income business was composed

of commissions and fees, which could enhance the profit of banks by expanding source of earning; Busch and Kick [13] discovered that noninterest income has positive correlation with ROE and ROA; Aggeler and Feldman [14] discovered that the profit of the bank depends mostly on noninterest income but not interest income as people generally expect. The Chinese scholars Sheng and Wang [15] think that the rise of the noninterest's proportion in total income can efficiently improve the performance of commercial banks. Goddard et al. [4] study the impact of revenue diversification of US credit unions on financial performance for the period 1993–2004. Their research finds that a positive direct exposure effect is outweighed by a negative indirect exposure effect for all but the largest credit unions. Sanya and Wolfe [16] use System-GMM and 226 listed banks in 11 emerging economies dating from 2000 to 2007 to explore diversification across and within both interest and noninterest income generating activities. Their research indicates that diversification decreases insolvency risk and enhances profitability. Saunders et al. [17] use 10,341 US banks as sample and conclude that a higher ratio of noninterest income to interest income is associated with a higher profitability across the banking sector. Nguyen et al. [10] carried out tests on 32 Vietnamese domestic banks with data period of 2005–2012. Their work concludes that banks with high noninterest income present lower risk than those with mainly interest income. A significant number of studies on US banking sector [2, 18] show that noninterest income unfavorably affects bank performance by either reducing return or increasing income volatility. However, the study by Saunders et al. [17] with a larger sample of US banks found noninterest income to be associated with higher profitability across all banks groups. Senyo et al. [9] found that noninterest revenue is becoming increasingly relevant and contributes to bank profit stability. Against the view that diversification may impact negatively on performance of banks, Abeyratna Gunasekarage et al. (2014) suggest that diversification of Australia's banks has improved their risk-return. Aslam et al. [19] show that noninterest income and business growth are positively related. Saunders et al. [20] find no convincing evidence that noninterest generating activities harm bank profitability and/or increase bank failure, insolvency, or systematic risks during both crisis and noncrisis periods.

Other researchers suggest that the influence of noninterest income on enhancing the profit of commercial banks is limited or even negatively correlated with performance. Smith et al. [21] argue that the increase of noninterest income cannot totally cover the income reduction. Jing Wang (2009) and Yu Liu and Jia Li (2012) suggest that noninterest income cannot improve the income rate. Research on the US banking system shows that as American banks convert from single business to mixed business, the variability also becomes more severe, which offsets profit coming from the income's diversification and therefore the shift towards noninterest income has not improved the risk-adjusted returns [11] (Hirtle and Stiroh, 2007). Furthermore some researches point out that the noninterest income and the banks' performance are actually negatively correlated and the volatility feature of noninterest income may even do harm to commercial banks' profitability [22, 23] (Jing Wang and Haowen Zhou, 2008; Chao Xue and Zheng li, 2014).

Other researchers show unclear or uncertain impacts from noninterest income. According to Stiroh and Rumble [18], there is no significant correlation between the noninterest income and the average rate of return. The European Central Bank's empirical test result shows that the relationship between performance and the noninterest income as a proportion of total income is uncertain. Yingchun Lou (2008) gives a similar conclusion.

There is a wide range of different conclusions from previous research about how noninterest income influences performance. As to the Chinese case, most researchers focus on only linear modelling approaches. This paper extends these approaches to consider nonlinear models using threshold values. We consider the following aspects: (1) we show the nonlinearity between noninterest income and performance of commercial banks and verify the existence of the threshold; (2) we consider the nonlinear impact of noninterest income on bank performance in different stages of scale using two thresholds; (3) we use data within 2007–2013 to ensure the consistency of the methods of calculation of some variables; the methodology for computation of these variables remained consistent during this period, and therefore our inferences are more robust.

3. How Noninterest Income Influences Commercial Banking Performance

3.1. Noninterest Income Business Expands Commercial Banks' Source of Revenue and Cost. The income source of commercial bank includes interest income and noninterest income. Obviously, when the expanding of traditional interest income business faces limitations from relatively stable population and increasingly intense horizontal competition, developing the noninterest income business becomes a main means to maintain and increase the total income level that has been experienced by international banks. Noninterest income can increase the total level of income of commercial banks in several ways: (1) satisfying diversified needs for financial services, investment consultation, and so forth by continuous innovation of new financial products and services in order to gain more fees and commission and strengthen the market competitiveness; (2) improving the investment level of commercial banks in financial markets to gain the investment income from bonds and stocks; (3) enriching income from gains or losses of exchange and profits or losses from changes of fair value and other business.

The operating costs of noninterest income mainly consist of labor costs, marketing expenses, and administrative expenses. When new noninterest financial products are released, the commercial banks have to pay much more to market new services than those invested in traditional interest income activities, and the operating costs will rise greatly. In addition, uncertainty in security market influences the returns of investment. Increasing the investment income requires the commercial bank to have sound investment ability. For some banks, poor ability of investing in the security market resulting from long time focusing on traditional activities may result in a poor performance in noninterest

income business. The loss in noninterest income activities will lead to loss in total revenue.

3.2. Noninterest Income Increases Volatility of Bank Earnings. Volatility brought by noninterest income of commercial banks has been highlighted in a previous literature. Some explain the impact of noninterest income on bank performance with portfolio theory: consistent with portfolio theory, an increased reliance on noninterest income is associated with higher volatility of returns. Similar conclusions have been drawn by Stiroh and Rumble [18], Calmès and Liu [24], Jaffar et al. [7], and Senyo et al. [9] who argue that the banks' greater reliance on noninterest income is associated with higher systemic risk. The results of these studies indicate noninterest income is much more volatile than interest income from a global viewpoint and for each individual bank. Deyoung and Roland [2] proposed three reasons to explain volatility induced by noninterest income on bank earnings. Firstly, switching costs of noninterest income are much lower than that of interest income because most fee-based activities are not relationship based, which contributes to the volatility. Secondly, noninterest income activities may require greater operating leverage than interest income activities because the main input needed to produce more fee-based products is typically fixed or quasi-fixed other than for interest expenses needed to produce more loans. Thirdly, noninterest income activities likely employ greater financial leverage than lending activities, because most noninterest income activities require holding little or no fixed assets and little or no regulatory capital. All these factors lead to volatility from noninterest income, increasing risk for commercial banks.

3.3. Noninterest Income Increases Operating Risk. Firstly, the expansion of noninterest income requires more investment in labor and facility, which leads to increasing operating costs. Thus, the larger operating leverage may induce larger operating risk. To acquire revenue from noninterest income, commercial banks have to invest much in both labor and facilities. These investments lead to high fixed costs. When industry profitability drops with competition among banks and the costs remain stable, the profit level drops sharply. Hence, in this case, high operating leverage will increase the operating risk.

Secondly, noninterest business increases commercial bank's operating risk while innovating new services and new products. During the process of developing noninterest business, it is necessary to create new services and new products along with the changes of costumers' needs. But with more kinds of business development, the management difficulty will increase as well as management cost. For example, the asset securitization products released by commercial banks can promote the circulation of asset, improve the liquidity, and also increase the risk of price fluctuation. In this case, high quality administration is required in commercial banks.

Finally, noninterest income business requires higher management ability, but Chinese banks may lack this expertise. Noninterest income will increase the existing risk of commercial banks. For example, if a commercial bank lacks the experience in the investment field when developing noninterest business, it will meet high investment risk. However, at present, the noninterest products of Chinese commercial banks mostly derive from traditional business, especially when client resources are depending on the long-term building up of traditional business.

Noninterest income can lead to commercial banks' overall income increasing in the initial stage of development. But as the scale expands the marginal cost of developing noninterest income is rising and the marginal income of noninterest income is decreasing, so the rising operating costs will decrease the net income. Huang and Chen [25] find that the banks with either relatively higher or lower ratios of noninterest incomes to operating incomes perform more cost-efficiently during the examination periods. Another view [26] holds that if the proportion of commission in total income is much too high, the total profit will decrease. Noninterest income's influence on the commercial bank's performance may have constraints, and the interaction between noninterest income and interest income must be managed.

4. Methodology

4.1. Threshold Effect Model. To account for the potential variability in the relationship between noninterest income and performance across different commercial banks, we allow for a turning point or a "threshold" within our model. The threshold effect refers to such a state; namely, when an economic parameter reaches a specific value, it will lead to another model parameter's alteration. The specific value is called threshold value. The regression model based on this effect is called the threshold regression model. If the modelled data contains multiple individuals and multiple years, the model is a panel threshold model. We use the model of Hansen [27]. Compared with the former threshold effect regression model, the Hansen [27] threshold regression model has two advantages: firstly, this threshold regression model does not need to separate the endogenous variables and the exogenous variables, so the threshold and the estimated parameters depend only on the endogeneity; secondly, the threshold model theory offers an asymptotic distribution theory to determine the confidence interval of the parameters and to estimate the threshold's statistical significance.

Based on the hypothesis above, this paper applies the panel threshold model of Hansen [27] to study the relationship between the bank's performance and noninterest income. The specific single threshold model is as follows:

$$\begin{aligned} y_{it} &= u_i + x_{it}'\beta_1 + e_{it}, \quad q_{it} \le \gamma, \\ y_{it} &= u_i + x_{it}'\beta_2 + e_{it}, \quad q_{it} > \gamma. \end{aligned} \tag{1}$$

Among these, i denotes company and t denotes time, y_{it} is the response variable, x_{it} is $p \times 1$ order explanatory variable vector, and q_{it} is the threshold variable. We use return on equity as the response variable performance measure and noninterest income as a proportion of total operating income as the main explanatory variable. The remaining explanatory variables are described in Section 4.3.

We also take the noninterest income proportion for the threshold variable. The role of the threshold variable is to

Table 1: The explanation of the model variables.

Category	Variable		Calculation of the variable	Explanation
Explained variable	Performance	ROE	Net profit/net asset	The performance of profitability
Explanatory variable	Noninterest income	NIR	Noninterest income/total operating income	How much and how well banks carry out noninterest business
Control variable	Bad loan ratio (BAD)		Nonperforming loans/balance of loans	The credit assets' security condition
	Capital adequacy ratio (CAR)		Capital/risk-weighted asset	How well the risk control ability is
	Cost ratio (COST)		Operating cost/operating income	Ability of control of the cost

divide the samples into different groups and the turning point of the regime changing. The different regimes in the model can be denoted into two states; in one state the threshold variable is bigger than the specific threshold; in the other the threshold variable is smaller than the specific threshold.

Define dummy variable $d_i(\gamma) = (q_i \leq \gamma)$. $(\cdot)$ is the indicator function, which means when $q_i \leq \gamma$, $(\cdot) = 1$, or $(\cdot) = 0$. This way, the equations above can be expressed by a single equation:

$$y_{it} = u_i + x'_{it}\beta + x'_{it}d_{it}(\gamma)\theta + e_{it}, \quad e_{it} \sim \text{iid}\left(0, \sigma^2\right). \tag{2}$$

Thereinto, $\beta = \beta_2$; $\theta = \beta_1 - \beta_2$. Using any threshold value γ, we can get the model fit and determine the residual sum of squares (RSS). Following Hansen [27], we take the optimal threshold $\widehat{\gamma}$ as the value that minimizes the RSS.

4.2. The Test of Threshold Effect Model. Test of the model includes two aspects: one is significance test of the threshold effect; the other is equivalence test between the estimator and its real value. The first null hypothesis we consider is $H_0 : \beta_1 = \beta_2$, and the test statistic is

$$F_1 = \frac{S_0 - S_1(\widehat{\gamma})}{\widehat{\sigma}^2}. \tag{3}$$

In formula (3), S_0 is the RSS obtained under the hypothesis H_0. Under the null hypothesis H_0, the threshold value γ cannot be identified, so the statistical distribution of F_1 is not standard. To solve this problem, we use bootstrapping to approximate the asymptotic distribution and then build the P value. The second null hypothesis we consider is $H_0 : \widehat{\gamma} = \gamma_0$, and the corresponding maximum likelihood ratio statistic is

$$\text{LR}_1(\gamma) = \frac{S(\gamma) - S(\widehat{\gamma})}{\widehat{\sigma}^2}. \tag{4}$$

The statistical distribution is also not standard. Nonetheless, Hansen [27] offers a simple formula to calculate a rejection region. When $\text{LR}_1(\gamma) \leq c(\alpha)$, we cannot reject the null hypothesis, where $c(\alpha) = -2\ln(1 - \sqrt{1-\alpha})$ and where α is the significance level.

4.3. Data and Indicators. This paper analyses a dataset containing 16 listed commercial banks, covering the period of 2007 to 2013. This includes 5 state owned commercial banks, 8 joint-equity commercial banks, and 3 municipal commercial banks. The resources of data are Almanac of China's Finance and Banking, the public annual report of each commercial bank, and the BankScope database.

There are three types of variables in this paper: commercial bank's performance (the dependent variable), the noninterest income as a proportion of total income, and other control variates (see Table 1). We use return on equity (ROE) to represent the performance of commercial banks. The reason is that, according to the DuPont formula,

$$\begin{aligned} \text{ROE} &= \frac{\text{net profit}}{\text{net equity}} \\ &= \left(\frac{\text{net profit}}{\text{operating income}}\right) * \left(\frac{\text{operating income}}{\text{total asset}}\right) \\ &\quad * \left(\frac{\text{total asset}}{\text{net equity}}\right) \\ &= \text{profit margin} * \text{asset turnover} * \text{leverage}. \end{aligned} \tag{5}$$

In the DuPont formula, the profit margin reflects the ability of the bank to earn profit and control costs. The asset turnover reflects the efficiency of capital operation. Therefore, it is reasonable to choose ROE as the indicator of commercial bank's performance.

In total the dataset includes five variables for the period of 2007 to 2013: ROE (return on equity), NIR (the noninterest income as a proportion of total income), BAD (nonperforming loan ratio), CAR (capital adequacy ratio), and COST (cost ratio).

As to the explanatory variables, we set NIR as the main explanatory variable, to reflect how much and how well those commercial banks carry out noninterest business; it also has indirect impact on the scale of noninterest rate business to the whole business. We choose nonperforming loan ratio (BAD) to reflect the security condition of credit assets. The less the ratio of nonperforming loan is, the safer the operation of banks is and the more the support noninterest rate business will get from interest rate business. CAR shows how well the commercial banks manage risk control, and COST reflects the ability of commercial bank to control costs. A lower level of the cost ratio indicates the ability to provide resources for noninterest income business.

The estimation model under single threshold condition is as follows:

$$\begin{aligned} \mathrm{ROE}_{it} &= u_{it} + \beta_1 \mathrm{BAD}_{it} + \beta_2 \mathrm{COST}_{it} + \beta_3 \mathrm{CAR}_{it} \\ &\quad + \beta_4 \mathrm{NIR}_{it} \ (q_{it} \le \gamma) + \beta_5 \mathrm{NIR}_{it} \ (q_{it} > \gamma) \\ &\quad + e_{it} \quad e_{it} \sim \mathrm{iid}\left(0, \sigma^2\right). \end{aligned} \tag{6}$$

4.4. Descriptive Statistical Analysis. In this section we consider descriptive statistics for every variable in the dataset and also consider separately the relevant variables of state owned commercial banks, joint-equity commercial banks, and municipal commercial banks.

4.4.1. Return on Equity (ROE). The mean ROE of joint-equity commercial banks across all years (21.26%) is higher than the mean for the other two kinds of banks and is also higher than the mean of all 16 commercial banks (19.19%). The highest ROE is 41.12%, coming from China Everbright Bank in year 2007. The state owned commercial banks and joint-equity commercial banks' mean ROE are 19.08% and 17.06%, respectively. The performance of city commercial banks is much worse than state owned commercial banks and joint-equity commercial banks, among which the highest ROE is merely 17.35%. However, the statistical standard deviation of the variables shows that municipal commercial banks are more stable than state owned commercial banks and joint-equity commercial banks, although the ROE of municipal commercial banks is comparatively lower. Those joint-equity commercial banks have highest ROE but fluctuate much more than other kinds of banks.

4.4.2. Nonincome Return Proportion. The state owned commercial banks' average NIR across all years is 20.45% which is the highest among the three kinds of commercial banks. Joint-equity commercial banks' NIR (15.05%) takes the second place, 4.66% lower than that of the overall mean. This is mostly because state owned commercial banks are predominant in scale and market share and have massive customer resources in the traditional deposits and loans business. In this case, the noninterest business can be developed much easier for state owned banks. Inevitably, the higher noninterest income is associated with higher volatility. Joint-equity commercial banks' performance is better than state owned banks, but their NIR is lower than state owned commercial banks, which indicates that the higher noninterest income rate does not necessarily lead to better performance. To some extent, this validates our earlier assumption about the relationship between noninterest income and performance.

4.4.3. Control Variates. This paper selects BAD, CAR, and COST as the control variates. It is found that, except for state owned commercial banks, both the nonperforming loan ratios of joint-equity commercial banks and municipal commercial banks are lower than the overall mean. Among these, the nonperforming loan ratio of municipal commercial bank is the lowest (0.97%), and the standard deviation is also the lowest. As for cost control, average cost ratio for 16 listed commercial banks across all years is 34.46%. The cost ratios of state owned commercial banks, joint-equity commercial banks, and municipal commercial banks are 22.70%, 36.12%, and 31.19%, respectively. Among these, the cost ratio of joint-equity commercial bank is higher than the mean value. As for risk control, the capital adequacy ratio for municipal commercial banks is much higher than that for joint-equity commercial banks. The Bank of Nanjing has the largest CAR in any year: 30.67% in 2007. This shows that municipal commercial banks are relatively conservative on risk management. On the one hand it is because their scales are relatively small, and the deposits and loans business is limited; on the other hand, according to their relatively lower noninterest income, the expansion of commission and fee business is also limited. Meanwhile, there municipal commercial banks also meet gaps with state owned banks and joint-equity commercial banks in investment management.

Table 2: The stationary test LLC result.

Variable	LLC test			
	Coefficient	t-value	t-star	$P > t$
ROE	−0.90519	−19.427	−15.51336	0.0000***
NIR	−0.99370	−18.402	−17.63716	0.0000***
BAD	−0.28727	−11.725	−8.16048	0.0000***
CAR	−0.66458	−14.243	−13.49747	0.0000***
COST	−0.60142	−10.544	−7.58969	0.0000***

Notes. ∗ ∗ ∗ denotes significance at 1% level.

5. Empirical Results and Analysis

5.1. Variable Stationary Test. We usually have to make sure that every variable is stationary when using the panel threshold regression model. So we should test the stationarity of the variable, which is known as a panel unit root test, using LLC as the test method. The test results are shown in Table 2. The null hypothesis of the LLC is H_0: there exist unit roots. According to the P value of variable ROE, NIR, BAD, and CAR, we make the conclusion that the null hypothesis should be rejected, and there are no unit roots.

5.2. Endogeneity Test. An explanatory variable's endogeneity could lead to the estimation bias. To avoid any possible endogenous variable problems, we use the Hausman endogenous test method (see Table 3) to test the explanatory variables.

Fe is the coefficient of the fixed effect. Re is the coefficient of random effect. According to the null hypothesis, there is no systematic difference between the fixed effect and random effect coefficients. Table 3 gives an overall P value of 0.4473. We accept the null hypothesis that no endogeneity exists in the explanatory variables.

5.3. Threshold Value Test. When using panel data to estimate threshold model, we should first define the quantity of the thresholds, which is also the quantity of structural change points, to determine the specific form of the model. We consider that, as the noninterest income rate changes, there

Table 3: Endogeneity test result.

Variable	(b) fe	(B) re	($b - B$) Difference	sqrt(diag($V_b - V_B$)) SE
BAD	−0.8938821	−0.8729335	−0.0209486	0.0827101
COST	−0.1579967	−0.194983	0.0369863	0.0755033
CAR	−0.4142893	−0.5194039	0.1051146	0.0974391
NIR	−0.1971864	−0.1767028	−0.0204837	0.0602813

b = consistent under $H0$ and Ha, obtained from xtreg.
B = inconsistent under Ha and efficient under $H0$, obtained from xtreg.
Test. $H0$: difference in coefficients not systematic.
chi2 (4) = $(b - B)[(V_b - V_B)^{\wedge}(-1)](b - B)$= 3.71.
Prob > chi2 = 0.4473.

Table 4: Threshold test results.

Model	F-statistic	P value	The frequency of bootstrap	Critical value		
				1%	5%	10%
Single threshold	24.5959***	0.0000	1000	6.86629	4.16177	2.83850
Double threshold	11.1334***	0.0020	1000	6.54412	3.62866	2.71744
Triple threshold	5.9955**	0.0180	1000	5.92804	3.51374	2.59486

Note. ∗ ∗ ∗ and ∗∗ separately denote the significance at 1% and 5% level.

may be up to three structural change points (thresholds) between noninterest income and the performance. We estimate the models, and test for existence of change points using the F-statistic and the associated P value derived from 1000 bootstrap replications. These are shown in Table 4.

From Table 4, the F-statistics for single threshold, double threshold, and triple threshold are 24.5959, 11.1334, and 5.9955, respectively. Single threshold and double threshold models are both significant at 1% level, and the bootstrap P values are 0.0000 and 0.0020; the triple threshold is only significant at 5% level. We use a 1% level and therefore employ a double threshold model.

The estimated thresholds for the double threshold model are 0.0998 and 0.1662. This means that the effect of noninterest income on performance of commercial banks will change structurally when noninterest income rate is lower than 9.98%, between 9.98% and 16.62%, and higher than 16.62%.

For comparison purposes we fit both the no threshold model and the double threshold model. The parameter estimates are shown in Tables 5 and 6. From Table 5 under the no threshold model, at 5% significance level, the significant negative coefficients are merely nonperforming loan ratio (BAD) and CAR. The coefficients of COST and NIT are also negative but not significant at the 5% level, although the coefficient of NIT is significant at the 10% level.

Intuitively, the higher the NIT is, the better the performance of commercial bank will be. However, the no threshold model shows that NIT and the performance are negatively related. The reason can be summarized as follows: the operating expenses deriving from noninterest income business are much higher than that of the interest income business. The interest income derives from loan business. From the current situation, management and cost control level for loan business cannot be further improved. So the marginal cost of interest income is quite low and barely grows after the interest income increases. However the noninterest income has been newly developed in the last 10 years. Compared to the loan business management and cost control level, these emerging businesses still have a long way to go. Moreover, banks investment income and exchange earning are influenced by secondary market and foreign exchange market price fluctuation, so negative profits are common, which means that deficits often happen in these two operations even though human and material resources have been allocated. The composition of the above two factors causes the higher expenses of acquiring noninterest income than interest income. Therefore, NIR can be negatively correlated with bank performance.

On the other hand, the result of the no threshold model shows that the coefficient of noninterest is only significant at 10% level. This may be caused by the strict supervision of China Banking Regulatory Commission (CBRC). Some innovation applications of noninterest operation have been refused by CBRC with the consideration of unfavorable impacts on noninterest business. The constraints of the policy make the effect of noninterest operation on bank's performance more limited.

From Table 6, when we add the two threshold values, noninterest income ratio becomes significant. And the coefficients are significantly different in different threshold interval. When noninterest income ratio is less than 0.0998, the coefficient estimated by threshold model is −1.8229, which means the return on equity (ROE) is negatively correlated with noninterest income (NIR); when the noninterest income ratio is between 0.998 and 0.1662, the coefficient of noninterest income grows to −0.7525, but the correlation between ROE and NIR is still negative. When noninterest income

Table 5: Estimated results of no threshold model.

Explanatory variable	Coef	Std	t	Prob
BAD	−0.8939	0.2043	−4.3758	0.0000***
COST	−0.1580	0.1302	−1.2132	0.2281
CAR	−0.4143	0.1856	−2.2321	0.0280**
NIR	−0.1972	0.1013	−1.9458	0.0547*

Note. ***, **, and * separately denote the significance at 1%, 5%, and 10% level.

Table 6: Estimates of double threshold model.

Explanatory variable	Coef	Std	t	Prob
BAD	−0.8595	0.1771	−4.8516	0.0000***
COST	−0.0539	0.1121	−0.4805	0.6321
CAR	−0.4234	0.1628	−2.6010	0.0109**
NIR (<0.0998)	−1.8229	0.2784	−6.5482	0.0000***
NIR (0.0998~0.1662)	−0.7527	0.1562	−4.8202	0.0000***
NIR (>0.1662)	−0.5046	0.1042	−4.8443	0.0000***

Note. *** and ** separately denote the significance at 1% and 5% level.

ratio surpasses the second threshold 0.1662, the coefficient of noninterest income ratio grows further to 0.5046. As the noninterest ratio grows up, the negative effect of noninterest income reduces, which means the performance can be improved.

The reason why the coefficient of noninterest income ratio grows after noninterest income ratio and generates threshold effects can be summarized as follows.

Firstly, the average cost of noninterest business reduces after the noninterest business grows. At the initial period of commencing noninterest business, the investment is relatively high. The investment includes new manpower, the expense of product research, and marketing cost. However, when noninterest business has been finely developed, the bank only needs to maintain the clients and the system, so the operation cost reduces. Overall, the preparation of noninterest business is a massive investment, but when the business line is highly developed, the variable cost just slightly grows with volume growing, which means the fixed cost is high but the marginal cost is quite low. The reduction of average cost of noninterest business will improve the performance of commercial banks.

Secondly, the increase of noninterest income ratio will enhance the total asset turnover of commercial banks. Total asset turnover is equal to net operation income within a certain period divided by total average assets of that period. Compared with loan operation, the main character of noninterest business is that noninterest business is not linked with assets, while the income from loans is linked with assets of the bank. In this way, on the development of banks, the rising rate of the interest income is remarkably similar to the average rising rate of total assets. So, when the noninterest income ratio rises, the numerator of total asset turnover grows faster than denominator, so the total asset turnover can be improved. From DuPont formula, ROE is a product of 3 different parts: total asset turnover, return on sales, and leverage ratio. So, when the rise of the noninterest income ratio makes the total asset turnover improve, the performance can be also improved.

6. Conclusion

Generally noninterest income of Chinese commercial banks is influenced by regulations from the central bank, techniques, and innovation. Faced with intensified competition induced by increasingly open market policies of China, Chinese commercial banks strive to compete in noninterest income activities. This paper analyses whether the noninterest income activities help enhance the banks' performance. Starting with the hypothesis of a threshold effect from noninterest income business on commercial banks' performance, this paper builds empirical model of the threshold effect and evaluates the threshold value. This indicates the following: (1) noninterest rate is negatively correlated with the performance of commercial bank; the higher the noninterest rate is, the lower the performance of commercial bank will be; (2) two thresholds are 0.0998 and 0.1662, which shows that the influence of noninterest income business on commercial banks performance has structural change in three intervals: lower than 9.98%, between 9.98% and 16.62%, and higher than 16.62%.

When noninterest rate is higher than the two threshold values, the negative relationship will weaken, so that when noninterest income reaches that point it will improve the relative performance. Our research also shows the coefficient between noninterest income rate and performance inclines to zero as the noninterest income rises. This suggests that when noninterest income reaches higher threshold, the negative relationship will gradually recede, and the coefficient may even become positive, which means the increase of noninterest income may improve the performance. So the policy implication of our research is to provide more resources to noninterest income activities and put more emphasis on the

quality supervision and efficiency supervision on noninterest income activities.

Competing Interests

The authors declare that they have no competing interests.

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Research Article

Model and Simulation of Network Crisis Information Diffusion under Uncertain Environment

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Network crisis information diffusion will have a certain impact on the public's psychology and behavior and will cause harm to the normal operation social of the public system and the effective allocation of the public resources. So we should timely control the key factors which affect the diffusion process to reduce the damage. Using cellular automata theory, the paper views the public as a series of cellular automata and sets up some cellular state evolution rules. With the help of MATLAB simulated evolution, this paper explores the diffusion rule of crisis information diffusion process and finds out the key factors of crisis information diffusion process and its influence on the diffusion scale and effect, so as to put forward coping strategies. It is hoped that this paper provides reference for the theoretical study of the crisis information diffusion and provides suggestion for the real world to control the crisis information diffusion.

1. Introduction

Since the 21st century, natural disasters, the financial crisis, public health, social security, and other kinds of crisis events are staged all over the world. The spread and diffusion of crisis information from above crisis events have certain effect on public's psychology and behavior. Under adverse circumstances that information acquisition is not sufficient and the situation is uncertain, crisis information diffusion will make the core values of decision makers seriously threatened and challenged and will cause harm to the normal operation social of the public system and the effective allocation of the public resources. Also, crisis information diffusion will lead to interruption or paralysis of certain social activities and even affect human security and social stability.

Based on cellular automata theory (cellular automata, hereinafter referred to as CA), this paper makes use of the BASS model in the field of new product or innovation diffusion to the process of crisis information diffusion and constructs the network crisis information diffusion system. Then this paper analyzes the diffusion motivation on the basis of system elements, determines the key factors, and constructs the transformation rules of crisis information diffusion state and studies its effect on the scale and effect of crisis information diffusion and analyzes the influence rules and effect factors of every factor. It is hoped that this paper improves the crisis information diffusion theory research and provides the corresponding countermeasures and measures of the crisis information diffusion control in the real world in order to reduce the risk of crisis information.

2. Network Crisis Information Diffusion System

2.1. Diffusion System. The network crisis information diffusion system is a complex integrated system composed of source, sink, crisis information, noise, diffusion media, and other elements, and it is a complex function system to realize the information diffusion between the source and the sink. The source and the sink exist in social network; they are the sender and receiver of crisis information. Crisis information attached to the critical incident is the main object of the diffusion process, and it contains the real and

objective information and the false rumors. Noise is the information which has the interference function in the social environment. Diffusion media or channel is the way of crisis information diffusion, and different diffusion media will affect the effect of diffusion. Government agencies and public media are the third party that publishes real information and guides public opinion. They can spread the official authority information through various channels in the crisis information diffusion process, control the spread of rumors, and reduce the risk of rumors.

In this paper, the one meaning of network is that the network provides a rapid means of rapid diffusion to information diffusion. Mobile Internet provides a variety of convenient communication and makes all kinds of information diffusion stride across the limit of time and space and speed diffusion rapidly in a short time. The other meaning of network is the complex networks composed of the complex interpersonal relationships of individuals in reality [1]. It takes the individual in reality as a point, takes the link between the individual as a side, and makes use of side to connect the points. Then it will form a complex relationship network map.

2.2. Crisis Information Diffusion Motive. Diffusion motive is the source power that drives crisis information diffusing. From the perspective of origin, diffusion motive includes informational motive, emotional motive, and social motive [2].

2.2.1. Informational Motive. Informational motive is subdivided into government informational motive, media informational motive, and public informational motive. The purpose is to meet the needs of the public information. Responsibility drives news media and government departments to diffuse information. Public informational motive is an altruistic behavior in social psychology.

Government Informational Motive. The coordination function, control function, and supervisory function of the government require the government to ensure that people can effectively accomplish the administrative goal and guide and supervise the production and life of the society. So, in the crisis, the government must have a correct understanding of the crisis information and correct guidance.

Media Informational Motive. Information diffusion, knowledge promotion, and supervision of public opinion are the function of the media. The key function is that media should timely disseminate the real information, explore the typical and advanced things in real life, extensively and lastingly promotion knowledge, promote the exchange and innovation of knowledge, and then influence the public's mode of production and life. Also, media should adhere to the responsibilities of public opinion supervision, expose the social contradictions and evil, and reflect the fairness and justice.

Public Informational Motive. From the perspective of social psychology, public altruism is a kind of self-satisfaction. When the public is in panic, sadness, tension, and other negative feelings, helping behavior is conducive to eliminate the negative feelings of the heart, and the person in the crisis and the potential victims will have these negative feelings. Psychological experiments show that even if the helper does not receive in return, we will still help people who are in need of help. This is the embodiment of social responsibility and moral. Also this reflects that the public's own demand for information is the internal driving mechanism that the public get or learn about crisis information.

2.2.2. Emotional Motive. It is the motive that releasing crisis information is in order to give vent to emotion. After the crisis, the individual is prone to anxiety, panic, depression, and other negative emotions. At this time, the public can transfer his feel to acquaintances or strangers in the mobile terminal in order to weaken and vent their dissatisfaction.

2.2.3. Social Motive. It is the crisis information diffusion driven by social factors. Social motive includes seeking the public's help, winning the attention of others, and gaining the public recognition. When you are in trouble in a crisis, you can release information through the network and inform others and hope to get effective help. Winning the attention of others is that you can release crisis information to get more attention by curiosity when the crisis is not yet clear [3]. After the crisis, the public release information to gain recognition. That is to say, the so-called opinion leaders published their judgment and evaluation of the crisis, which can get the user's respect and praise.

2.3. Network Crisis Information Diffusion Process. In the early period of the crisis, the information is only in the hands of a small number of insiders. The large-scale diffusion through media is unlikely to happen. The entire diffusion network is in a calm state, and the information flow is very small.

With the evolution of time, people's demand for the crisis information is more and more, and crisis information owners' information will be released to the surrounding population through social networks. At the same time, government agencies, experts, scholars, and the media will also be involved, and the authoritative information is also released to the public. The amount of crisis information is great at this time and the information content is true or false. People will judge the type of information that is trusted according to the status of neighboring nodes and the amount of their information.

Then government agencies investigate and survey and take corresponding measures to control the situation, which makes the strength of the information flow of authoritative information increase. The crisis is gradually transparent, the deviation and error information are clarified, and the spread of rumors decreases. Public panic begins to eliminate, the need for information decreases, and the attention of the crisis is also slowly reduced. At this time, the amount of information is large, and the proportion of authoritative information content gradually increased.

Finally, the crisis has been fully resolved, and the social values and norms of behavior return to normal. The crisis information diffusion is ended.

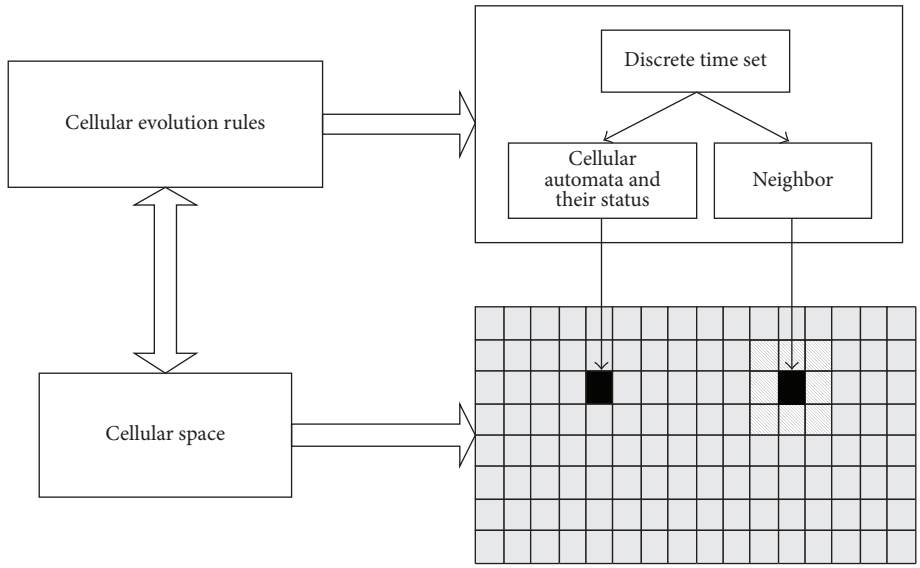


Figure 1: CA Composition.

3. Evolution Model Building

3.1. The CA Model. CA is composed of cellular space, cell (lattice), neighbor, cellular evolution rules, and finite cell state $(S_1, S_2, \ldots, S_k)$ (Figure 1).

$$A = \left(L_d, S, N, f\right). \tag{1}$$

In the above formula [4], A is CA system (cell is the basic unit of CA and is the research object of CA system). L_d is cellular space (d is space dimension) and is the collection of cellular distribution space. S is the set of cellular automata finite discrete state. N is the set of neighbor cells which affect the next time state of the central cell. f is the cellular state transition function, which represents the central cell state evolution rule from the current time to the next [5].

3.2. Bass Model Assumptions. According to the BASS model and the purpose of the simulation, we need to make the following assumptions.

(1) After the crisis, the information from the crisis includes the real information and the false information (rumor), and the other information may not be discussed [6]. Media and the public are likely to become the two kinds of information dissemination. The media and individuals have three possible states for two kinds of information; they are adoption, no adoption, and wait-and-see.

(2) S indicates the above three states of the individual. $S = 1$ indicates that the individual adopts the real information. $S = 0$ indicates that the individual takes wait-and-see attitude to crisis information. $S = -1$ indicates that the individual adopts the rumors. The initial attitude of the individual to crisis information is decided by the individual's subjective consciousness.

(3) In the crisis information diffusion system, the largest scale of the total number of evolutionary individuals is certain, but the number of people who adopt crisis information is changing over time.

(4) In each evolution, the media and individuals have the right to change their own state. Media accepts the government's supervision and management and the people's supervision. So the attitude of the media to the crisis or the adoption state requires timely adjustment. For the public, its state is affected by three aspects [7]; one is the government, the second is the media, and the third is the surrounding neighbors.

(5) The state of the media is influenced by government's regulation and public reputation, and the state of the individual is influenced by the surrounding neighbors, the government, and the media. The degree of impact may not be the same, and it is represented by the weight.

(6) The government agency has the national credibility, so its attitude is generally cautious, and its state will not make regular adjustments. We consider that the state of the government is certain. In view of the government's aim of serving the people, it is assumed that the publicity information is accurate and true.

3.3. Network Crisis Information Diffusion Model Building

3.3.1. The Cellular Space (L_d). It is assumed that cellular space is the whole system of crisis information diffusion. This model uses the $100 * 100$ model to construct the cellular space; row and column intersection represents the potential

adopters of crisis information, so the number of individuals is involved in the evolution of the 10000.

3.3.2. Cell. Each information demander or social individual is a cell. It is supposed that the whole diffusion system is divided into a set of square grids, each grid point representing an information need, and that it is a unit cell. A cell is a potential crisis information adopter; then we can use the ordered pair (i, j) to express $(i = 1, 2, \ldots, 100; j = 1, 2, \ldots, 100)$. It is the potential adopters' position in the cellular space, and the cellular (i, j) represents the individual in the j column of the i column in the cellular space.

3.3.3. The Set of Cellular State. This model determines the set of cellular state $S = \{-1, 0, 1\}$. The three kinds of cellular state express the three chosen states in the face of the real (false) information. −1 indicates that the individual chooses to adopt the false information. 0 indicates that the individual is in a state of wait-and-see, and 1 indicates that the individual chooses to adopt the true information.

3.3.4. The Neighbor Form. A cell takes the cellular around it as its neighbor. In CA model, for two-dimensional cellular automata model, the most common is the Von Neumann type and the Moore type. Here we are using the Moore type. The state of the central individual or central element in the time $t + 1$ is affected by the 8 neighbors around t. Cellular neighborhood is not the neighbor relationship in the model [8], and it is very complex. The distance between neighbors may be very far away, but the existence of the network can reduce or even eliminate the information lag distance.

3.4. Evolution Function and Cellular Evolution Rules. The state of a cell in the time $t + 1$ depends on its own and its surrounding neighbors' state and the corresponding transformation rules.

$$S_{ij}^{t+1} = F\left(S_{ij}^{t}, \Omega_{ij}, R\right). \tag{2}$$

S_{ij}^{t+1} and S_{ij}^{t} refer to the state of the $t + 1$ moment and the t moment in the position of ij, Ω_{ij} refers to the set of the surrounding neighbors' state collection, and R refers to a series of transformation rules.

Whether individual transform adoption state into no adoption is affected by the internal and external factors. The mathematics expression is as follows:

$$f(t+1) = I(t+1) + O(t+1). \tag{3}$$

In this formula, $I(t+1)$ is the internal factors. We assumes that individuals involved in the evolution have the ability to obtain information. So we should only consider the information needs of individual, and the individual information needs is the information requirements of individual expresses (C).

Compared with the internal factors, external factors are expressed as $O(t + 1)$. We select the choice of information from the government credibility (G), the media influence (E), and other people around individual (8 neighbors) as external influence factors [9]. Individual state transformation probability [10] is

$$\begin{aligned} p_{ij}^{t+1} &= \frac{f(t+1)}{\max\left(f(t+1)\right)} \\ &= \frac{G(t+1) + E(t+1) + C(t+1) + V(t)}{\max\left(G(t+1) + E(t+1) + C(t+1) + V(t)\right)}. \end{aligned} \tag{4}$$

Individual adoption behavior is influenced by the society (government credibility, media influence) and individual cognition of crisis information (information needs, neighbors' state). In the information adoption behavior model (IABM), there is positive correlation between individual adoption behavior and social influence, individual information cognition, and the influence degree from social influence; individual information cognition to individual adoption behavior is 0.6. That is to say, when the factors want to change individual adoption behavior, the individual state transition probability should reach 0.6. Accordingly, when the individual state transition probability is not up to 0.6, individual state is in a wait or not to adopt, and when the individual state transition probability is higher than 0.6, the adoption state will change. Wait state is the transition state of adoption of different information, and when the individual state transition probability is between 0.2 and 0.6, individual state is in a wait, and when the individual state transition probability is not up to 0.2, individual state is not to adopt. Thus the individual state transition probability is divided into three categories, and the transformation rules are as shown in Table 1.

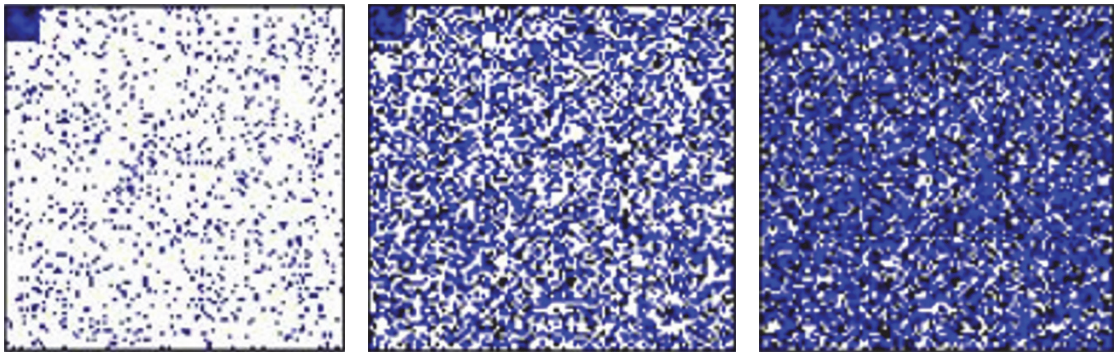
Table 1: Transformation rules table.

State before the conversion	Transformation rules	The transformed state
$S(t) = -1$	$0 < p_{ij}^{t+1} \le 0.2$	$S(t) = -1$
	$0.2 < p_{ij}^{t+1} \le 0.6$ [10]	$S(t) = 0$
	$0.6 < p_{ij}^{t+1} \le 1$	$S(t) = 1$
$S(t) = 0$	$0 < p_{ij}^{t+1} \le 0.2$	$S(t) = -1$
	$0.2 < p_{ij}^{t+1} \le 0.6$ [10]	$S(t) = 0$
	$0.6 < p_{ij}^{t+1} \le 1$	$S(t) = 1$
$S(t) = 1$	$0 < p_{ij}^{t+1} \le 0.2$	$S(t) = -1$
	$0.2 < p_{ij}^{t+1} \le 0.6$ [10]	$S(t) = 0$
	$0.6 < p_{ij}^{t+1} \le 1$	$S(t) = 1$

4. The Simulation and the Analysis of the Results

According to the above transformation rules, we suppose the initial state of the cellular is set to 0, and set the number of potentially affected people is $N = 10000$.

In the evolution model, the initial state of cellular is assigned randomly the values 1 and 0 according to the proportion of 1 : 100. That is to say, in the early days of crisis, there was only the wait-and-see crowd and a small number of



$t = 10$ $t = 30$ $t = 100$

Figure 2: The initial evolution.

people who knew the actual information. And the emergence of the rumors is delay in the time; then trust rumors crowd in the process of evolution appear. In the event of a crisis, there is difference in number between the wait-and-see people and the people who know the truth. We simulate the influence on the effect of crisis information diffusion from the different initial state value of individual information needs C, the government's credibility G, and the media influence E. Each simulation runs 100 times.

After the initial value is set, its evolution process is shown in Figure 2. White represents the potential adopters of crisis information, the blue represents the true information adopters, and the black represents the false information adopters (the evolution graphics when $t = 10$, $t = 30$, and $t = 100$).

4.1. The Influence of the Degree of Individual Information Demand on the Diffusion Process of Crisis Information. Assuming that the values of the government credibility and media influence are set, we simulate the crisis information diffusion process by changing the degree of individual crisis information demand C. This is the crisis information adoption process of the individual. Because the influence of diffusion effect is mainly caused by the adoption behavior, so the whole evolution process is only applicable to the adoption crowd, and the wait-and-see state is only the excessive process of adoption. The evolution simulations run five times. We set the government credibility $G = 0.5$ and the media influence $I = 0.5$ which remain unchanged. That is to say, the government credibility and the media influence are in the stable medium level. And the values of individual information demand C are 0.1, 0.3, 0.5, 0.7, and 0.9. According to the different values of individual information demand C, the total number of individuals who adopt the crisis information changes, as shown in Figure 3.

It is assumed that the government credibility and the media influence are at a moderate level.

(a) When $C = 0.1$, the individual information need is average distribution between 0 and 0.1. And when the degree of information of individual demand is low, the number of people impacted by crisis information is low. Then the majority of people are in the wait-and-see state, and they are not concerned about or interested in the crisis information.

(b) When the value of C is from 0.3 to 0.5 and from 0.5 to 0.7, the changing of the number of three kinds users shows that the number of the wait-and-see people is declining with the rising of individual information demand, and the number of the adopters is increasing. This shows that the individual's adoption of crisis information will increase with the increase of the information demand. In addition, when $C = 0.9$, when the individual has a strong demand for information, the evolution results show that the final number of the affected people reaches 90%. When the public is very concerned about the crisis, the number of the affected people is relatively more.

4.2. The Influence of the Government Credibility on the Diffusion Process of Crisis Information. Assuming that the values of the degree of individual crisis information demand C and the media influence E are set, we simulate the trend of individual choice to adopt crisis information by changing the government credibility G. We set the degree of individual crisis information demand $C = 0.5$ and the media influence $E = 0.5$. And the values of the government credibility G are 0.1, 0.3, 0.5, 0.7, and 0.9 [11]. According to the different values of G, the number of individuals who choose to adopt true and false information is changing as shown in Figure 4.

By observing the changes of the number, we assume that the individual crisis information demand and the media influence keep stable.

(a) During the period of crisis information diffusion, when $G = 0.1$, that is to say that the credibility of the government is low, and we find that a small number of people who adopt real information begin rising after the evolution of 100 times. Then the false information appears; the number of people who adopt the false information is more and more in the case of less intervention by authoritative organizations, even more than the number of people who adopt the real information. Because of the lack of authoritative

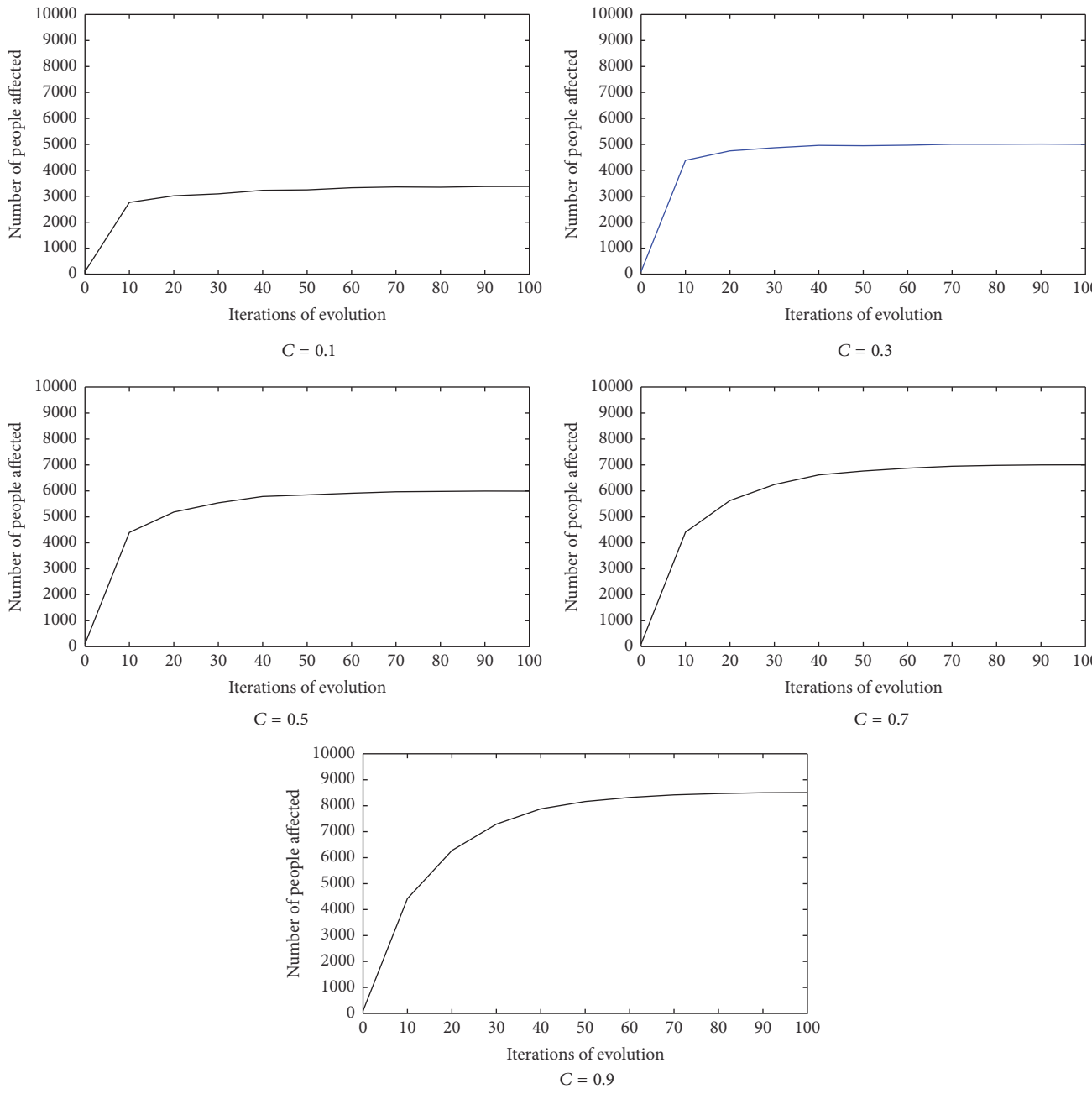


Figure 3: The total number of individuals to adopt information.

information on the release and support, the number of people to adopt the real information increases is decreasing, while the number of adopters to rumors is increasing, and the upward momentum is obvious. This shows that the number of people to adopt the real information is more than the number of people to adopt rumors; if the government takes the ignore attitude, it may lead to the rapid increase of the number of rumors. When the number of adopter to rumors is more than the number of adopter to the real information at a certain time, this will cause the great panic and form the unpredictable hazards.

(b) When the value of the government credibility is from 0.1 up to 0.3, it can be seen that the number of people to adopt the real information and the number of people to adopt the rumors are increasing and tend to be stable. The government intervention and propaganda play a key role in inhibiting the rumors, and the number of adopter to the real information in the diffusion process is more than the number of adopter to rumors. With G increasing from 0.3 to 0.5, 0.7, 0.9, the quantity gap between the adopter to the real information and the adopter to rumors is widening. It shows that the government information release

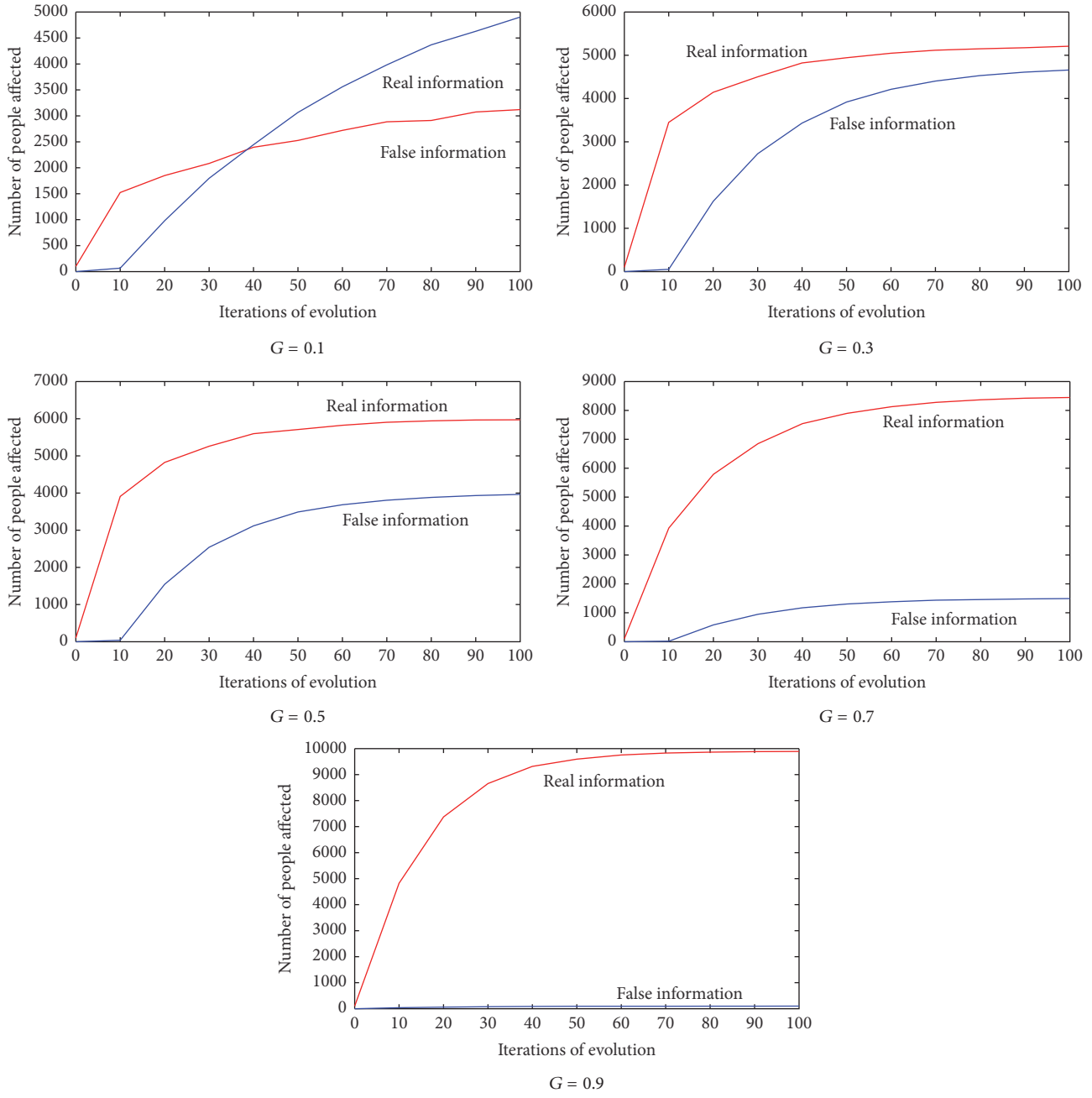


Figure 4: The number of individuals to adopt the real or false information.

behavior makes the wait-and-see people gradually trust the true information of the authority, which greatly inhibited the rumors spread and diffusion.

4.3. The Influence of the Media Influence on the Diffusion Process of Crisis Information. Assuming that the values of the degree of individual crisis information demand C and the government credibility G are set, we simulate the trend of individual choice to adopt crisis information by changing the media influence E. Because the media influence is supervised by the public opinion and the government, so the media's impetus to the information is built on the basis of the former two. We set individual crisis information demand $C = 0.5$ and the government credibility $G = 0.5$. In Figure 5, when the government credibility G and the media influence E are 0.5, the extent of their impact has been great. Taking the upper limit of $E = 0.9$ [12], we can see that the media influence is under the government credibility, strengthening the propaganda. We should strengthen publicity; then the media influence can have a driving effect on the crisis information diffusion [13].

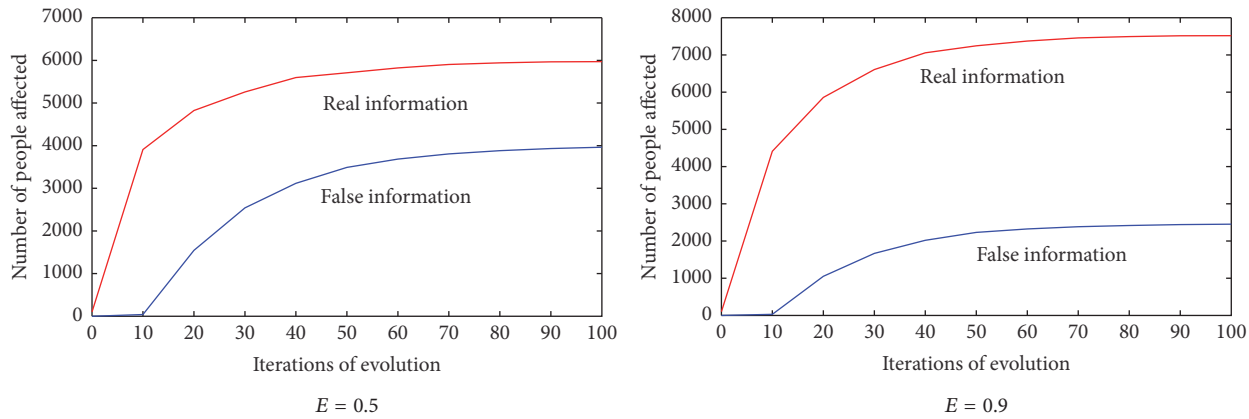


Figure 5: Different values of E have effect on crisis information diffusion.

5. Countermeasures

5.1. Strengthen the Publicity of Government and Other Authoritative Organizations and Media. The government's response to the crisis information diffusion, the government's intervention, and the release of real information are necessary and critical, and the government's propaganda time should be judged according to the actual situation. The publicity of the government will help the public to grasp the real information and guide the network information. When the crisis information is mainly the real information, the government may conduct propaganda in a later time or not conduct propaganda. And when the crisis information is mainly the false information, the government's guidance has a key guiding role on the diffusion result. After the crisis, the crisis information will appear in the network at the first time. At this time, the government should use the Internet platform to publish relevant information of public crisis through official channels or media platform [14], in order to avoid the rapid spread of the false information.

5.2. Strengthen the Supervision of the Diffusion Channels. "The government cannot develop without credit," this is to say that the public trust is essential to the government construction. This requires that the government should establish the relevant accountability mechanisms and severely punish criminals who diffuse false information on the Internet platform to create panic and then increase the intensity of punishment. For the crisis information diffusion, the government should actively guide and strengthen supervision and then make the information diffusion in the direction of the good communication. The government should formulate the basic guidance and supervision strategy of public crisis information diffusion network. Also the government should dynamically adjust according to the actual situation of information diffusion and sum up the coping strategy according to the implementation results. The government has accumulated the experience to deal with the public crisis information diffusion in the network, in order to improve the coping ability of network information.

5.3. Improve the Accuracy and Authority of Information. When the media influence of the regular diffusion becomes larger, the number of the right information adopters is increasing. Therefore, during the crisis, expanding the coverage of the official formal media channels and speeding up the correct information transmission speed can effectively curb false information spread. At the same time, the extension of the real information dissemination scale can improve the accuracy of information. We should establish a healthy and orderly information release mechanism, improve the accuracy and the authority of the information, standardize information dissemination form, combined with influential media organizations to release information, and then spread scale accurate information. Also, we should strengthen the supervision of public opinion and reduce the distortion of the crisis information in the diffusion process.

5.4. Strengthen Public Emergency Quality Education. In the initial state of the crisis information diffusion, the number of people who adopt the real information and the rumors in the crisis information is closely related to the information diffusion effect. We can improve public emergency quality education by spreading the knowledge of all kinds of crisis and popularizing all kinds of crisis management knowledge. On the one hand, it can reduce the number of manufacturing rumors and solve the problem from the source. On the other hand, it can make the potential impact population increase the ability to distinguish and deal with rumors, in order to suppress the spread of rumors.

6. Conclusion

After the crisis, the crisis information will spread and diffuse through a variety of channels, and the information which eventually reaches the public will have the right information and the rumors. On the basis of the CA model, this paper constructs the diffusion model of the correct information and the rumor information and analyzes the difference of the diffusion regulation and the diffusion state of the two kinds of information under different parameters. The

research results show that the factor affecting the scale of the crisis information diffusion is mainly the public's demand for information, and the two kinds of information diffusion are mainly influenced by the government credibility and the media influence. Based on this, this paper puts forward the countermeasures. This paper makes simulation analysis about the two types of crisis information diffusion in different parameters and how to combine the actual problem to further optimize the model is the follow-up research work.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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Research Article

Research on the Uncertainty Decision Model of the Regional Collaborative Innovation System Based on an Improved Ant Colony Algorithm

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The regional collaborative innovation system is a nonlinear complex system, which has obvious uncertainty characteristics in the aspects of member selection and evolution. Ant colony algorithm, which can do the uncertainty collaborative optimization decision-making, is an effective tool to solve the uncertainty decision path selection problem. It can improve the cooperation efficiency of each subsystem and achieve the goal of effective cooperation. By analysing the collaborative evolution mechanisms of the regional innovation system, an evaluation index system for the regional collaborative innovation system is established considering the uncertainty of collaborative systems. The collaborative uncertainty decision model is constructed to determine the regional innovation system's collaborative innovation effectiveness. The improved ant colony algorithm with the pheromone evaporation model is applied to traversal optimization to identify the optimal solution of the regional collaborative innovation system. The collaboration capabilities of the ant colony include pheromone diffusion so that local updates are more flexible and the result is more rational. Finally, the method is applied to the regional collaborative innovation system.

1. Introduction

Collaborative innovation is a kind of integrated product development mode, which combines the human design method and the innovative technology. It is not only an individual's innovative behavior but also a kind of collective innovation [1–5]. The result of innovation can be a concept of design object, program, or entity model. Collaborative innovation is conducted to improve the desired function of production, accelerate the product development process, and make it have better economic characteristics. Collaborative innovation needs collaborative decision-making [6]. It is a procedure of multisubject participation. From a number of feasible solutions, it takes the collaborative decision group as the main body and does the quantitative and the qualitative analysis, in the order to choose the best one. There are 4 stages of collaborative decision-making process: (1) determining the collaborative criteria (target); (2) providing a number of feasibility collaborative programs; (3) doing quantitative treatment; (4) choosing the best plan. To improve reliability and dependability of analysis appraisal, it proposes the methods of grey relative analysis based on Analytic Hierarchy Process and develops the scheme analysis and evaluation system. Most research on collaborative innovation based on model evaluation at home and abroad uses an evaluation decision model based on results, mainly the Production Function Method, Analytic Hierarchy Process, Fuzzy Comprehensive Evaluation, DEA Method, Grey Evaluation Method, Matter-Element Analysis Method, Artificial Neural Network Method, Delphi Method, Comprehensive Index Method, and so forth. The research perspectives mainly concentrate on the national, regional, and other macroscopic evaluation decisions [7–9].

The innovation performance evaluation system of federal research institutions is representative, and the Government Performance and Results Act (GPRA) was formed as the framework and system foundation. It converted the performance evaluation from "input-output" into "target-results" mode. South Korea placed the direction of the development of science and technology as the core and measured the degree of project completion objectively through the inspection of project objective setting. The OECD put forward that the core of collaborative innovation evaluation and decision is inventory investment, technology, knowledge update and spillover effects, and so forth [10–14] from the perspective of the process of knowledge innovation. Pia Hurmelinna-Laukkanen and Pierre Barbaroux et al. researched collaborative innovation evaluation and decision from the angle of innovation main bodies.

On April 24, 2011, comrade Hu Jintao put forward explicitly that collaborative innovation should be promoted actively in a speech marking the one hundredth founding anniversary of Tsinghua University. Subsequently, the Ministry of Education and Ministry of Finance jointly issued a collaborative innovation program in the universities, which is referred to as the 2011 plan [15–17]. Chen Jin, Xiong Li, Xie Xuemei, and other scholars have researched collaborative innovation deeply from the angle of the collaborative evaluation decision of collaborative innovation. The economic competition of contemporary world is mainly manifested as the competition of science and technology. The social economic structure and economic relations and customs have changed dramatically during the era of knowledge economy. Regional innovation system is an effective tool for developing economics. Unlike other tools, regional innovation system is a more flexible policy tool. The evaluation of regional innovation system's performance can provide scientific basis for the judgment, establishment, and correction of regional policy. A lot of researchers note this. The studies are mainly concerned with the network organization, type, operation, and institutional reform of collaborative innovation based on the mechanisms of collaboration and of improvement. There is no too much work that utilizes mathematical modelling to study the improvement process of collaborative innovation capability [18–22].

In integrated domestic and foreign research, the research methods are mainly confined to the discussion and summary of experience. This research is basically concerned with the strategic objectives, organizational structure, system development, and other aspects of qualitative analysis. There is more qualitative analysis but less quantitative evaluation, and the quantitative evaluation model is only a general fit model. The lack of collaborative innovation design for the industry characteristics of the specialized collaborative innovation decision-making evaluation model is a major drawback. Research on collaborative innovation decision-making through an evaluation model is still rare. The ant colony algorithm has not been introduced into the research on collaborative innovation so far.

2. Uncertainty Decision Model Construction of the Regional Collaborative Innovation System

The regional innovation system is basically the same as the ant colony algorithm in many ways, such as the goal and process of uncertainty collaborative optimization decision-making. However, there is a big difference in the uncertainty of the system optimization decision path caused by the local factors' alteration [23–25]. Therefore, this paper establishes an ant colony model based on pheromone diffusion to reflect the pheromone. This model can improve the cooperation ability of collaborative innovation system in the direction of evolution path selection, further optimize the balance and load of resources in the regional innovation system, and speed up the process of collaborative decision-making. Under the guidance of ant colony optimization model, it is possible to enhance the value of innovation and improve the regional innovation system's innovation efficiency.

2.1. Model Building. Members of the regional collaborative innovation system (n universities, m scientific research institutes, p enterprises, and q participating members of other innovative technologies such as government financial institutions) achieved innovation improvement through collaboration, that is, more efficient innovation, shorter innovation cycles, and stronger knowledge transfer capabilities. Collaboration can produce two types of driving modes: first, theoretical innovations are achieved by the internals of universities through collaborative innovation in some subjects. Second, the ultimate goals of more efficient innovation, shorter innovation cycles, and stronger knowledge transfer capabilities are achieved through institutional innovation by the original organization [26–28].

To facilitate the analysis, C is defined as the regional collaborative innovation system, $S = \{S_1, S_2, \ldots, S_n\}$ is defined as a subsystem of universities, $R = \{R_1, R_2, \ldots, R_m\}$ is defined as a subsystem of scientific research institutes, $E = \{E_1, E_2, \ldots, E_p\}$ is defined as a subsystem of enterprises, and $O = \{O_1, O_2, \ldots, O_q\}$ is defined as a subsystem of others. The collaborative mechanism of care comprises S, R, E, and O. Because of the characteristics of uncertainty, instability, and nonlinearity in the coordination mechanism, the regional collaborative innovation system C will be influenced by itself and the external environment. The complex changes in overall status, structure, and functional effects in C will happen according to the basic principles of synergetics. Material, energy, information exchange, and collaboration exist in internal subsystems and also between systems and the external environment; therefore, system instability can be used to describe the evolution processes, and evolution regularity can be grasped through identifying the order parameters of the regional collaborative innovation system [29].

To further simplify the discussion, cofactor F is introduced; then, regional collaborative innovation systems are abstracted as in type 1:

$$C = F\{S, R, E, O\}. \quad (1)$$

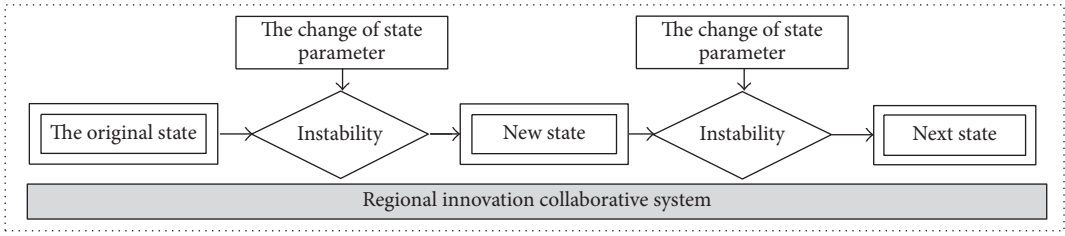

Figure 1: Instability analysis of a regional collaborative innovation system.

The essence of collaborative mechanisms is looking for an effective collaborative solution $f_S, f_R, f_E, f_O \in F$ based on the structure functional characteristics of the composite system such that the overall performance $V(C)$ of the regional collaborative innovation system C is greater than the performance $V(S)$ plus $V(R)$ plus $V(E)$ plus $V(O)$ and $V(C)$ can obtain its maximum:

$$\max \quad \left\{ V^F(C) - \left(\sum_{i=1}^{n} V^{f_S}(S) + \sum_{i=1}^{m} V^{f_R}(R) + \sum_{i=1}^{p} V^{f_E}(E) + \sum_{i=1}^{q} V^{f_O}(O) \right) \right\}. \tag{2}$$

Q is defined as the status parameter of the complex system, Q_0, Q_1 are defined as the initial state condition of the system and evolution constraints, and the sets of f_S, f_R, f_E, f_O are F; then, formula (2) is as follows:

$$\text{st.} \quad \begin{cases} q \in Q_0 \\ f_S(q), f_R(q), f_E(q), f_O(q) \in Q_1 \\ f_S, f_R, f_E, f_O \in F. \end{cases} \tag{3}$$

2.2. State Parameter Analysis and Model Evaluation. The instability of the regional innovation system is a general characteristic of a complex system. When the control parameter reaches a critical value, the system will lose stability and transition into an unstable state until the emergence of a new stable state.

Figure 1 shows the evolution processes of the regional innovation system. The critical control parameters are the state parameters of the system, where the state parameters show the nature and extent of order when the system has changed as shown in Figure 1.

A regional collaborative innovation system is a complex system, and, between the various subsystems, there is no simple linear relationship, but rather the mutual influence and mutual restriction of a nonlinear relationship. The evolution direction of the regional innovation system is multidirectional. In terms of its evaluation goal, members of the regional collaborative innovation system focus on different goals.

Universities efficiently use a variety of scientific and technological innovation resources (including personnel, organizations, equipment, facilities, funding, and other tangible resources, an innovative culture, policy mechanisms, and organizational management intangible resources). Many high level scientific and technological innovations (including papers, books, patents, and awards, as well as the direct results of innovative talents and achievements in the economic and social fields and other indirect results) are obtained through knowledge innovation, technological innovation, transformation and management innovation, and other scientific and technological innovation activities, and competitive advantages in science and technology and an innovation ability are formed.

For the scientific research institutes, technology innovation abilities are based on progress at the scientific research level and the diffusion abilities of innovation. The levels of scientific research are decided by the subject frontier and the visual original and whether there is a major breakthrough with the new discovery, invention, and technology. The diffusion of innovation ability mainly includes the innovation resources, talents, information, equipment, and policy from several aspects.

For the enterprises, technological innovation means improvements of product quality and market share, development of new products and services, and enhancements of profits by applying innovative knowledge and new technologies, processes, production methods, and management mode [30–32].

To a certain extent, universities pay more attention to the progress of innovation and scientific research, institutes pay more attention to the practical transformation of innovation, and enterprises pay more attention to the value of innovation. There are several evaluations for the collaborative innovation centre platform. It can be divided into three levels with dozens of indicator references [33]. Among them, this paper will regard the direct parameter of the influencing innovation index after collaborative optimization as the basis of evaluation. In the regional collaborative innovation system, organic coordination among different subsystems makes innovation more efficient; see Table 1.

Table 1: Evaluation index of the regional collaborative innovation system.

First-level evaluation index	Weight	Second-level evaluation index	Weight	Third-level evaluation index	Unit	Weight
Conditions for innovation	20%	Human resources	35%	R&D staff (1)	People	18%
				Technological staff (2)	People	16%
				Production and business staff (3)	People	6%
				Other staff (4)	People	5%
				Number of senior staff/total staff	%	20%
				Number of master and doctorate/total staff	%	15%
				Academic leaders	People	20%
		Financial resources	25%	Project funding	Ten thousand yuan	25%
				Business funding	Ten thousand yuan	18%
				Other funding	Ten thousand yuan	15%
				Per funding	Ten thousand yuan/People	42%
		Material (equipment) resources	40%	Number of scientific research platforms at national, provincial level		35%
				Innovative devices over 1 million	Ten thousand yuan	25%
				Use of scientific equipment	%	40%
Achievements in scientific research	25%	Achievements in scientific research	100%	Number of research projects completed	Item	23%
				Number of scientific and technological awards at provincial level	Item	27%
				Number of invention patents	Item	33%
				Number of SCI/SSCI	Paper	17%
Innovation benefits	35%	Achievement transformation	30%	Leadership adopted (instructions), patent implementation, and achievements transformation	Item	42%
				Business income of member enterprise	Ten thousand yuan	11%
				Percentage share of business income of joint investment of social capital	Ten thousand yuan	6%
				Rate of transformation	%	41%
		Public service	30%	Service of platform for the public		38%
				Penetration of public service	%	29%
				Effective growth rate	%	33%
		Efficiency of innovation	40%	Human input-output ratio	%	33%
				Financial input-output ratio	%	44%
				Material input-output ratio	%	23%
Cooperative level	20%	Development planning	45%	Planning and construction of subjects		56%
				Implementation of research programs		44%
		System construction	25%	Establishment of collaborative system		55%
				System implementation		45%
		Organizational culture	30%	Incentives at all levels	Item	67%
				Spiritual rewards	Item	33%

2.3. Indicator Processing. For a more detailed description, the evaluation of creative ability is a normalized quantization process; parameters affecting innovation indicators based on collaborative optimization are used for the evaluation basis. Definitions are given below:

C'_{ij}(value)—evaluation function of innovation value.

C'_{ij}(time)—evaluation function of innovation cycles.

C'_{ij}(effciency)—evaluation function of innovation efficiency.

Without taking into account other relevant factors, the overall performance $V(C)$ of the regional collaborative innovation system C in formula (2) is converted into the following formula:

$$V^F(C) = \xi_1 C'_{ij}(\text{value}) + \xi_2 C'_{ij}(\text{time}) + \xi_3 C'_{ij}(\text{effciency}). \tag{4}$$

ξ_1, ξ_2, ξ_3 represent the weight functions. Obviously, C'_{ij}(value) and C'_{ij}(effciency) are positive indicators (the higher the value is, the stronger the capacity is). C'_{ij}(time) is a negative indicator (the higher the value is, the poorer the ability is). Because the dimensions of the evaluation function are not the same, the index matrix $V^F(C)$ must be normalized.

Order

$$x_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{m} \left(a_{ij}\right)^2}}. \tag{5}$$

When A is a negative indicator

$$x_{ij} = \frac{-a_{ij}}{\sqrt{\sum_{i=1}^{n} \left(a_{ij}\right)^2}}, \tag{6}$$

$$x_j^+ = \max\left\{x_{ij}\right\},$$

$$x_j^- = \min\left\{x_{ij}\right\}, \tag{7}$$

$$(j = 1, 2, \ldots, n).$$

The sets of the optimal values are $V^F(C)^+ = \{x_1^+, x_2^+, \ldots, x_n^+\}$.

The sets of the worst values are $V^F(C)^- = \{x_1^-, x_2^-, \ldots, x_n^-\}$.

Based on the related principles of the osculation value model, a satisfactory system performance value is the point closest to the sets of optimal values and the maximum distance from the sets of the worst values.

Then, the osculation value of $V^F(C)$ is

$$C_i = \frac{d_i^+}{d^+} - \frac{d_i^-}{d^-}, \tag{8}$$

where

$$d_i^+ = \left[\sum_{j=1}^{n} \left(x_{ij} - x_j^+\right)^2\right]^{1/2},$$

$$d_i^- = \left[\sum_{j=1}^{n} \left(x_{ij} - x_j^-\right)^2\right]^{1/2}, \tag{9}$$

$$d^+ = \min\left\{d_i^+\right\},$$

$$d^- = \max\left\{d_i^-\right\},$$

and d_i^+ and d_i^- indicate the Euclidean distances between solution A_i and the optimal solution A^+ and worst solution A^-. d^+ is the minimum among the most advantageous m; d^- is the maximum among the worst m.

C_i reflects the degree of deviation of the performance of regional collaborative innovation system $V^F(C)$ from the most advantageous performance. When $C_i = 0$, $V^F(C)$ is closest to the most advantageous thing. For the range of values of $C_i > 0$, $V^F(C)$ deviates from the most advantageous. The range of values of $C_i > 0$ will be used as a measure. Then, when C_i is a minimum value, the collaborative optimization model is the most satisfactory model [34].

3. Model of Collaborative Uncertainty Decision

To further describe the collaborative optimization mechanism of multiple subsystems and give full play to the institutional innovation system and resource advantages, the improved Ant Colony Algorithm is introduced to improve system performance innovation $V^F(C)$. In the improved ant colony algorithm, a volatilization model is introduced in the process of pheromone partial updates and the number of outstanding ants is increased in the process of the global updates. With this algorithm, the shortcomings of the basic ant colony optimization algorithm, such as slower convergence speed and ease of convergence to a local optimal solution, are improved [35].

3.1. Pheromone Diffusion Model. An ant colony algorithm based on the pheromone diffusion model is proposed, and pheromone diffusion rules are given by scholars. The optimization abilities of this algorithm are close to the real behavior of ants, but the pheromone diffusion model construction is relatively complex and the local pheromone update mechanism is missing. In this case, a simplified efficient pheromone diffusion model is constructed as shown in Figure 2.

Pheromones will diffuse within a circle with centre O and radius r, as shown in Figure 2. If there is a point l in the circle, then the pheromone concentration received by l is determined by

$$\frac{\tau_O}{r} = \frac{\tau_l}{r - d_l}. \tag{10}$$

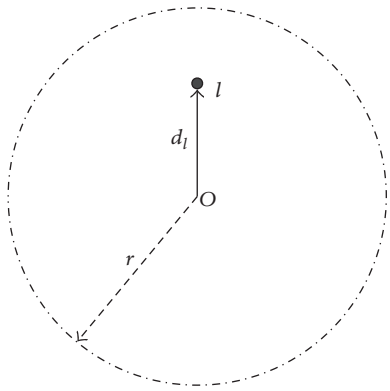

Figure 2: The pheromone evaporation model.

Assumptions. The position of the ant is O, and the concentration of the pheromone is τ.

3.2. Local Pheromone Update Mechanism. In the process of crawling, ants will diffuse pheromones to the path nearby through traverse points. If ant k traverses between two points i and j and the distance is d_{ij}, then the ant k will diffuse pheromones according to the pheromone diffusion model in Figure 2. The pheromone diffusion concentration of the paths connecting (i, l) and (j, l) will be changed, and the changes are $\Delta\tau_{il}^k$ and $\Delta\tau_{jl}^k$. The formula derivation is as follows.

The pheromone diffusion concentration of ant m that traverses points i, j is $\tau_O = \mu\Delta\tau_{il}^k$, where $0 < \mu < 1$, diffusion radius $r = d_{ij}^2/\overline{d}$, and the average distance of all traversed points is $\overline{d}$. According to formula (10), $\Delta\tau_{il}^k$ and $\Delta\tau_{jl}^k$ can be expressed as

$$\Delta\tau_{il}^k = \begin{cases} \mu \cdot \dfrac{1}{l_{ib}} \cdot \left(1 - \dfrac{d_{il} \cdot \overline{d}}{d_{ij}^2}\right), & d_{il} < r, \\ 0, & \text{otherwise}, \end{cases}$$
$$\Delta\tau_{jl}^k = \begin{cases} \mu \cdot \dfrac{1}{l_{jb}} \cdot \left(1 - \dfrac{d_{jl} \cdot \overline{d}}{d_{ij}^2}\right), & d_{jl} < r, \\ 0, & \text{otherwise}. \end{cases} \tag{11}$$

In the proposed algorithm, formulas (7) and (8) are placed into the pheromone update formula (12):

$$\tau_{ij}(i+1) = (1-\rho)\,\tau_{ij}(t) + \rho\Delta\tau_{ij}^k, \tag{12}$$

$$\Delta\tau_{ij}^k = \begin{cases} \dfrac{1}{l_{jb}}, & \text{when the ant } k \text{ is through the city } ij, \\ 0, & \text{otherwise}. \end{cases} \tag{13}$$

Here, ρ represents the pheromone diffusion factor, $1 - \rho$ represents the residual factor, $\rho \in [0, 1]$, and l_{jb} represents the path length travelled from the initial city to the current city.

Thus, compared to the pheromone update mechanism of the basic ant colony algorithm, the new pheromone diffusion can display better collaboration ability between ants, and the convergence speed is accelerated.

3.3. Collaborative Uncertainty Decision Model Calculations. The collaborative pheromone update methodology is adopted in the moving process of ants, which speeds up the local optimization of the algorithm and simultaneously increases the likelihood of local convergence. To avoid local minima, a random disturbance is introduced and used to change the global pheromone update mechanism of the basic ant colony algorithm and prevent the algorithm from premature convergence or stagnation in the process of ant path finding. The overall algorithm framework is shown in Figure 3.

The specific steps of the algorithm design are as follows.

Step 1 (parameter initialization). Collaborative innovation evaluation index matrix information is read, and the values of the initial evaluation indices are added to the taboo table. $V^F(C)$ and fitness value table of osculation value C_i are obtained.

Step 2 (selection of the next evaluation traverse points according to the probability). The transition probabilities of traverse points are calculated based on formulas (12) and (13), and the next traverse point j is selected based on roulette rules and put into taboo table. Then, the values of $V^F(C)$ and C_i will be calculated, the retention policy based on eliteness will be implemented, and the fitness value table will also be updated.

Step 3 (local pheromone update). The corresponding path pheromone based on formulas (11) will be updated according to the pheromone diffusion model.

Step 4. If the taboo table of ant k is not full, go to Step 2.

Step 5 (global pheromone update). When all of the evaluation matrix is traversed by m ants, $V^F(C)$ and C_i will be calculated and the optimal solution will be updated. The best solution in this cycle is selected and the global pheromone updated.

Step 6. If the termination conditions are met, the calculation will be stopped and the optimal solution will be outputted.

4. Example Verification

To fully validate the science, feasibility, and effectiveness of the model, model analysis and collaborative optimization calculation for "CICOST" have been implemented. The regional collaborative innovation system comprises universities within the industry, research institutes with strong research capabilities, and sizeable enterprises with strong scientific research, and, among them, the universities are the main members and the others general members. The main data of the collaborative innovation model are shown in Table 1.

The three types of osculating value curves indicate that three types of problems increase with increasing number of evaluation indices of innovation efficiency, as shown in Figure 4.

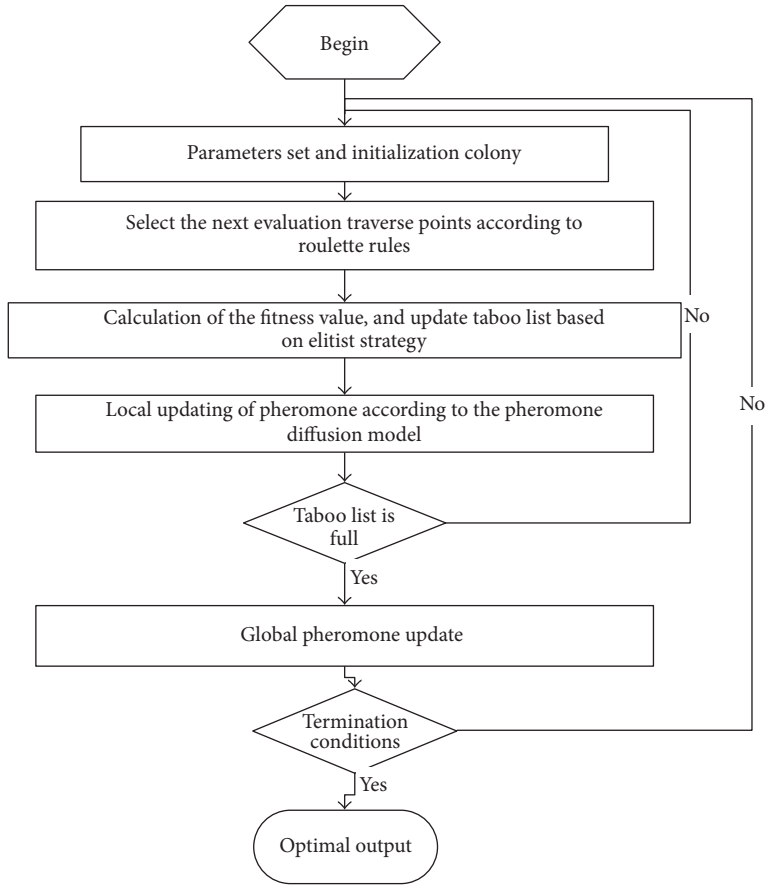

Figure 3: Algorithm framework.

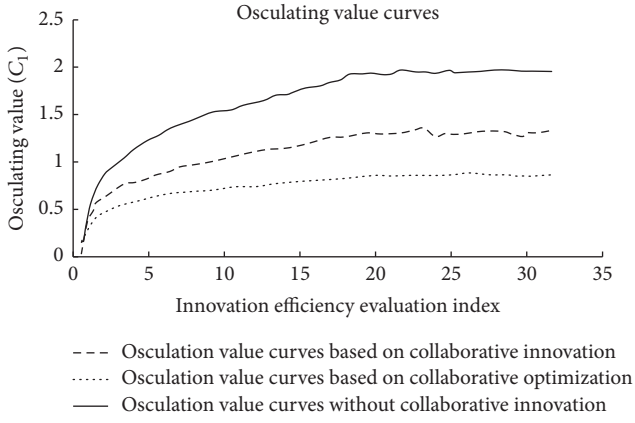

Figure 4: Osculation value curve.

The final calculation results are given in Table 2.

Noncollaborative innovation refers to members not integrated to form a regional collaborative innovation system, the collaborative model refers to members who become an innovative collaborative innovation system through mutual cooperation, and the optimized collaborative model refers to each member with the highest efficiency synergies. The Euclidean distance between the most optimized point and the index evaluation value is expressed as d_i^+, and the Euclidean distance between the worst point and the index evaluation value is expressed as d_i^-. The osculation value between the most optimized point and innovation evaluation performance $V^F(C)$ is expressed as C_i.

Table 1 shows that the innovation performance of noncollaborative innovation is 0.641, that of the collaborative innovation model is 0.720, and that of the optimized collaborative model is 0.854, which is much better than 0.720. Figure 3 results show that the best performance of the regional collaborative innovation system is obtained when the improved ant colony algorithm is used to solve the collaborative optimization problem in this paper, and as the scale of the problem is larger, the advantage is more obvious.

The effectiveness of the algorithm in optimizing the regional collaborative innovation system is analysed through the iterative curve shown in Figure 5. The basic parameters of the ant colony algorithm are set to $m = 30$, $\lambda = 5$, $\alpha = 1$, $\beta = 2$, $q_0 = 0.96$, $\rho = 0.58$, and $\mu = 0.37$. After 500 iterative calculations, the fitness value converges to 0.854, and the elapsed time is 12150 ms. This shows that a good solution and a good convergence speed of the algorithm can be obtained when solving optimization problems of a collaborative innovation system. Simultaneously, the loads

Table 2: The results of the models.

Type	d_i^+	d_i^-	C_i	$V^F(C)$
Noncollaborative innovation	1.825	0.523	1.899	0.641
Collaborative innovation model C	0.728	0.576	1.341	0.720
Optimized collaborative innovation model C'	0.808	0.712	0.598	0.854

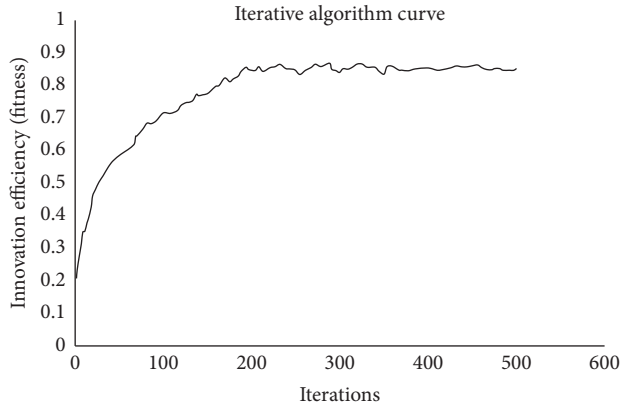

Figure 5: Convergence curve of algorithm search optimization.

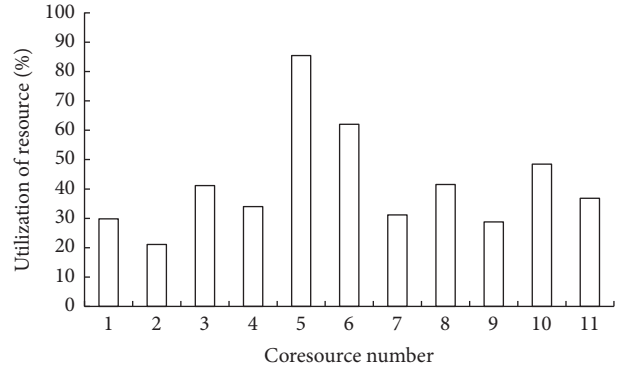

Figure 6: Load optimization of 11 class sharing resources of the collaborative innovation system.

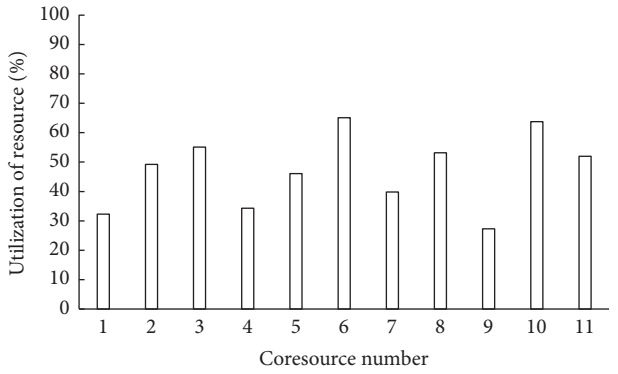

Figure 7: Optimized resources of the collaborative innovation system.

used for 11 class sharing resources were compared before and after optimization using the histograms in Figures 6 and 7, which show that the loads used for the resources are more balanced and that the overall resource utilizations are improved after collaborative optimization.

The evaluation results of the regional collaborative innovation system of "CICOST" show that "CICOST" takes leading industry and national development as its own duty and addressing the major needs of the country and the industry as a goal. It brings together domestic first-class universities and large enterprise groups with collaborative members making decisions. According to the significant scientific research task, it has produced a substantial collaboration, formed a collaborative innovation culture with active innovation and exploration and the establishment of a risk and benefit sharing system, and carried out scientific planning around major innovation tasks. It has made significant progress whether in the high level of team building, personnel training, science and technology awards, intellectual property rights, and so forth or in terms of institutional reform and other aspects, particularly in innovative exploration and reform of talent cultivation. The reform of the system is still in its initial stage, because it is a new innovation system. The aspects of the high level of cooperation in scientific and technological innovation, high level of talent and innovation team management system, high level personnel training system, and so on still need to strengthen.

5. Conclusion

Optimization analysis and an improved ant colony algorithm were implemented for the members of a collaborative innovation system. The algorithm, which improves the pheromone update mechanism and enhances the collaboration ability of ants in path selection, optimizes the balance of resources and loads of the system. Thus, if we select collaborative innovation members based on the ant colony algorithm, the technical strengths of cooperative members selected will be fully utilized, and, through an effective collaborative decision mechanism, the value of innovation will be promoted, the efficiency of innovation will be improved, and a scientific basis for collaborative uncertainty decision of cooperative members will be provided.

Disclosure

The authors declare that this work is the extension of the link paper entitled "A Verification Model of Collaborative Innovation Optimization System Based on Ant colony Algorithm."

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

A Decision Method to Maximize Service Quality under Budget Constraints: The Kano Study of a Chinese Machinery Manufacturer

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Manufacturers are increasingly facing keen competition and improving customers' position in the value chain. Many of them have made efforts to promote service quality and enhance customer satisfaction. Research is lacking in considering the trade-off between service costs and customer satisfaction when tackling service quality issues in the machinery industry. A decision method is proposed for maximizing service quality in machinery industry under budget constraints, from the perspective of enterprise capacity and customer satisfaction. Due to the strength of the Kano model in acknowledging the nonlinear impacts of quality elements on customer satisfaction, we formalize the relationship between customer satisfaction and sufficiency of service quality elements quantitatively. And then we develop a novel nonlinear programming model to maximize service quality under budget constraints. In particular, we implement our model at Xuzhou Construction Machinery Group Co., Ltd., one of the largest Chinese construction machinery companies, to validate the efficacy of the method.

1. Introduction

To meet complex customer requirements and respond quickly to increasing competition and technological developments, the machinery industry has recognized customer value as a source of competitive advantage [1]. The machinery industry produces and maintains machines for consumers, the industry, and other companies. Many machinery manufacturers transform themselves from being product-oriented companies to being service providers [2–4]. They believe effective service planning and high level of quality service delivery are necessary to improve operations efficiency and enhance competitive edge [5].

Indeed, the changing environment has led to a lot of machinery manufacturers to rethink their service strategies. The concept of service is not limited to after-sale service, it will be extended to cover the whole lifetime cycle. This includes the service components integrated into the process of delivery, consumption, and use. Researchers have used various expressions to refer to the escalation of services, for example, "servitisation" [6], "integrated solutions" [7], and product-service systems (PSS) [8–11]. Obviously, service is crucial for machine manufacturers to enhance customer value and gain additional business. To gain customer endorsement and loyalty, firms need to put efforts into service design to improve service quality [12].

Oliva and Kallenberg (2003) [2] highlighted the significance of service quality in satisfying and retaining customers in manufacturing industries, while Izogo and Ogba (2015) [12] believe customer's satisfaction of service quality is the determinant of customer loyalty. However, manufacturers offer services of varying scopes and degrees, and the service quality is significantly related to the specific service processes and service participants. To achieve high service quality,

one needs to understand the relationships between various service quality elements and other related elements, for example, processes, personnel, and resources [13].

The literatures have mainly focused on categorizing customer service requirements, planning, and designing proper service products to assure customer satisfaction. There is a lack of a systematic and quantitative verification scheme for service quality improvement, especially in the machinery industry. In general, services influence costs, and high service quality often leads to high service costs. It is therefore vital to strike a good balance between customer satisfaction and service costs when improving service quality in machinery industries, while researchers have not yet addressed this important issue enough. To make contributions to the existing literatures, we try to find out a solution of service quality improvement in machinery industries to leverage customer satisfaction and budget constraints from bilateral perspectives (customer satisfaction and service provider's capacity). Thus, the relationships between customer satisfaction, service costs, and service quality elements will be identified, and then a novel quantitative decision method will be set up to determine the priorities of service quality elements in quality improvement.

In an effort to propose a decision method to maximize the overall customer satisfaction under budget constraints, we formulate two research issues:

(1) In the machinery industry there is a limit on resources allocation to services. Most resources are focused on tangible products. There is still a need for a continuous improvement process in regard to service quality. So based on a bilateral prospective, how can this help to develop a systemic and quantitative framework to identify key service quality elements, detect the relationship among quality elements, and determine the improvement priorities for service transformation in machinery industries?

(2) The level of customer satisfaction depends on adequate supply of the service components, which relies on large monetary investment. Then, how can this help to develop a mathematical model balancing customer satisfaction and service costs and validate the results empirically?

The paper proceeds as follows. Section 2 covers a review of the literatures. Section 3 proposes the research framework. We implement the proposed model and its solution methodology to Xuzhou Construction Machinery Group Co., Ltd. (XCMG), the largest construction machinery company in China, in Section 4 and prove its validity. Research conclusions and future research are discussed in Section 5.

2. Literature Review

2.1. Kano's Model. Kano et al. (1984) [14] proposed the Kano model adapting Herzberg's "motivation-hygiene theory" [15]. This model demonstrates the nonlinear relationship between customer satisfaction and the performance of quality elements. And it classifies quality elements into five dimensions: must-be, one-dimensional, attractive, indifferent, and reverse, as shown in Figure 1.

The Kano model has been widely used for customers' needs analysis, decision-making analysis, and other management practices [16–18]. However, it has some disadvantages; that is, it uses qualitative analysis techniques and does not define the classification criteria explicitly in quality elements' classification. It also fails to account for the provider's concerns in terms of the capacity to fulfill the customer requirements [17].

Many studies tried to improve Kano's model for supporting product and service design in different ways. Through the quantitative analysis of Kano's model, Berger et al. (1993) [19] used two indicators of customer satisfaction (CS) and customer dissatisfaction (DS) to indicate the average impact of customer requirements on customer satisfaction. This improves Kano's model in understanding the influence about different categories of customer requirements on CS [20]. Further, Wang and Ji (2010) [21] proposed a novel approach to identify the relationships between customer satisfaction and the fulfillment of customer requirements (S-CR) in Kano's model, and it provided an effective way to integrate Kano's model to other mathematical model in engineering design process.

In addition, the traditional Kano survey forces customers to choose one answer for a particular question. This ignores the fuzzy and uncertainty factors related to human thinking when the questionnaire is being designed. Thus, some scholars proposed the fuzzy Kano model using integrated fuzzy set theory [22–24].

To improve Kano's model for decision support, literatures discussed the issues of integrating Kano model with other techniques. These techniques include SERVQUAL [25, 26], QFD [27–29], Importance-Performance Analysis (IPA) [30], and Kaisei engineering [31, 32]. It is very beneficial for improving Kano methodology [33].

2.2. Kano's Model in Service Quality Management. Understanding each category of the quality elements will be helpful in service quality management. Thus, the Kano model has been applied in various industries to classify service quality elements and make decisions in improving service quality. An overview of the reviewed literature in this theme is given in Table 1, encompassing authors, research focus, industry, and model type (theory, quantitative method, or empirical).

Previous research in the area has shown focus on service quality elements identification, evaluation, and classification. There has not been an emphasis on the decision-making method of service quality improvement. The small amount of research in this area dealt with qualitative analysis, and there is a dearth of quantitative research. Table 1 shows that the Kano model has a wide application in improving service quality in many industries. However, most of these applications are in the service business, and little research is focused on service quality in machinery enterprises.

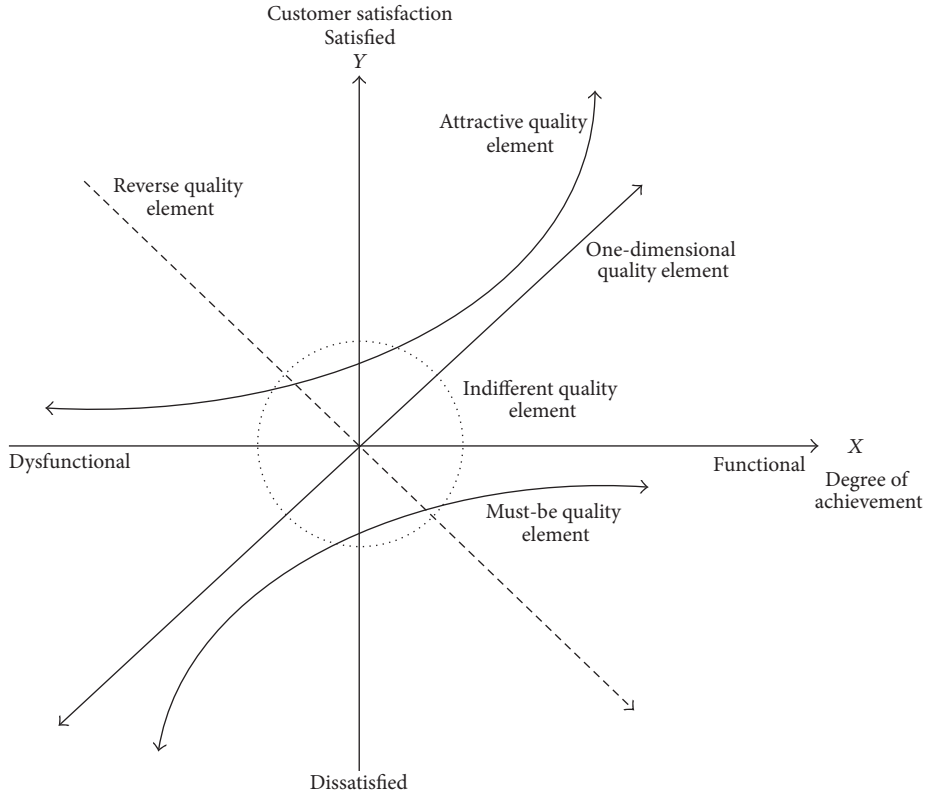

Figure 1: An overview of Kano model.

2.3. Conclusions on the Literatures. From the review of related literatures the following conclusions were drawn:

(1) The Kano model is an effective tool to identify and classify service quality elements whether in service product development or service quality improvement. But Kano model is still a qualitative method in nature, and setting up a quantitative Kano methodology would be beneficial to provide support for decisions more effectively.

(2) Service quality research has largely been focused on service business, leading to a dearth of research on service quality in machinery industries. Service quality is a critical element for machinery industries to gain and maintain competitive advantage, so it is meaningful to extend the application to machinery industries.

(3) Researchers stressed the importance of understanding service quality elements that have the greatest impact on customer satisfaction and promoting the priority of these quality elements. In the decision-making process for service quality improvement, the service provider's capacity needs to also be considered. Cost constraints are usually accommodated in the decision-making. The goal of the decision-making process is to seek a solution of service quality improvement that leverages customer satisfaction and the service provider's resource constraints.

3. Methodology

In this section, an integrated framework is proposed to maximize machinery industry service quality under budget constraints, by considering the trade-off between customer satisfaction and service costs. Figure 2 shows the proposed research framework with its subprocesses. These subprocesses include identification of service quality elements, division of market segmentation, Kano model survey, quantitative analysis of Kano model, and decision model formulation.

3.1. Identification of Service Quality Elements. Service quality elements extraction and identification are the foundation not only of the Kano model, but also of decision analysis in service quality improvement. Service qualities are different from general products with the distinctive features of intangibility, inseparability, heterogeneity, and perishability [53]. So it is very necessary to find an effective way to translate customer requirements into a set of service quality elements from the customer perspective. There are several methods that can be used to identify customer service quality elements, such as SERVQUAL model and QFD, which are currently thought of as useful methods to extract service quality elements by listening to the voice of customers [29].

3.2. Division of Market Segments. The division of market segments aims to find the appropriate target customers in the decision analysis process. As a rule, different customers have different utility expectations of service quality. At this point, the customer base is divided into several customer segments

Table 1: An overview of the reviewed literatures in this theme.

Authors	Research focus	Industry	Model type
Tan and Shen (2000) [27]	Integrating Kano model of QFD	Web page	Quantitative method
Erto and Vanacore (2002) [34]	Service quality measurement	Hotel service quality	Empirical
Ting and Chen (2002) [35]	Quality elements identification and classification	Hypermarket	Empirical
Kuo (2004) [30]	Classification of service quality attributes	Virtual community websites	Empirical
Yang (2005) [36]	Classification of service quality attributes	Technical products	Theory
Nilsson Witell and Fundin (2005) [37]	Dynamics of service attributes	E-service	Theory, empirical
Chang et al. (2006) [38]	Service quality improvement from customers' satisfaction perspective	Hospital services	Quantitative method
Chen et al. (2010) [39]	Service quality improvement by integrating Kano model of Six-Sigma	Stationary industry	Quantitative method
Chen and Lee (2009) [40]	Quality elements identification and classification	Chain convenient stores	Method, empirical
Kuo et al. (2009) [41]	Service quality measurement and classification	Mobile value-added services	Theory, empirical
Chen et al. (2009) [42]	Attractive quality elements discovering	Massively multiplayer online role-playing game	Method, empirical
Yang (2011) [43]	Quality elements identification	International certification service	Theory, empirical
Xie et al. (2010) [44]	Quality elements evaluation	NPO products	Empirical
Chen and Kuo (2011) [45]	Quality elements identification and classification	E-learning service	Empirical
Tsai et al. (2011) [46]	Potential service quality gaps discovery	Human resource service online agency	Method, empirical
Kuo et al. (2012) [47]	Service quality improvement decision using IPA-Kano model	Mobile service	Method, empirical
Florez-Lopez and Ramon-Jeronimo (2012) [48]	Quality elements identification and classification using fuzzy Kano model	Logistics service	Quantitative method
Tontini and Dagostin Picolo (2014) [49]	Quality elements interaction analysis based on psychological foundations	Pizzerias and video rental stores	Theory, empirical
F.-Y. Chen and S.-H. Chen (2014) [50]	Service quality improvement	Hot spring industry	Method, empirical
Bandyopadhyay et al. (2015) [51]	Classification of service quality attributes	Banking	Empirical
Esmaeili et al. (2015) [52]	A fuzzy method to assess and identify service quality attributes	Logistics service	Quantitative method
Meng et al. (2015) [24]	Decision method for service quality improvement	Logistics service	Method, empirical

according to their demographic information, psychographic data, and purchase behaviors. The different customer segments have distinguished characteristics about service quality perceptions. Effective marketing research and customer-tailored management actions are taken for each segment, guaranteeing an optimal level of customer satisfaction in different customer segments under budget constraints. Many methods and tools are available to assist the process including clustering, classification, self-organizing maps (SOM), evolutionary algorithms, interaction detection methods, and artificial neural networks [54].

3.3. Classification of Service Quality Elements Using the Fuzzy Kano Model. The Kano model provides a systematic way of service quality elements classification. It is based on three tools: the Kano questionnaire, the Kano evaluation table, and the Kano final results table [14]. The Kano questionnaire examines each service quality element with a pair of questions, functional and dysfunctional. There are five possible answers for each question, that is, "like," "must-be," "neutral," "live-with," and "dislike" [14]. According to the Kano evaluation table, for each respondent, the service quality element is classified as one of Kano categories. Generally, according to the Kano final results table, the most frequent observations of the sample set of responses are considered as the final category for the service quality element [14].

Generally, the traditional Kano model is lacking in processing the vagueness and uncertainties in human judgment and decision-making when surveying. Fuzzy set theory introduced by Zadeh (1965) has many advantages in analyzing

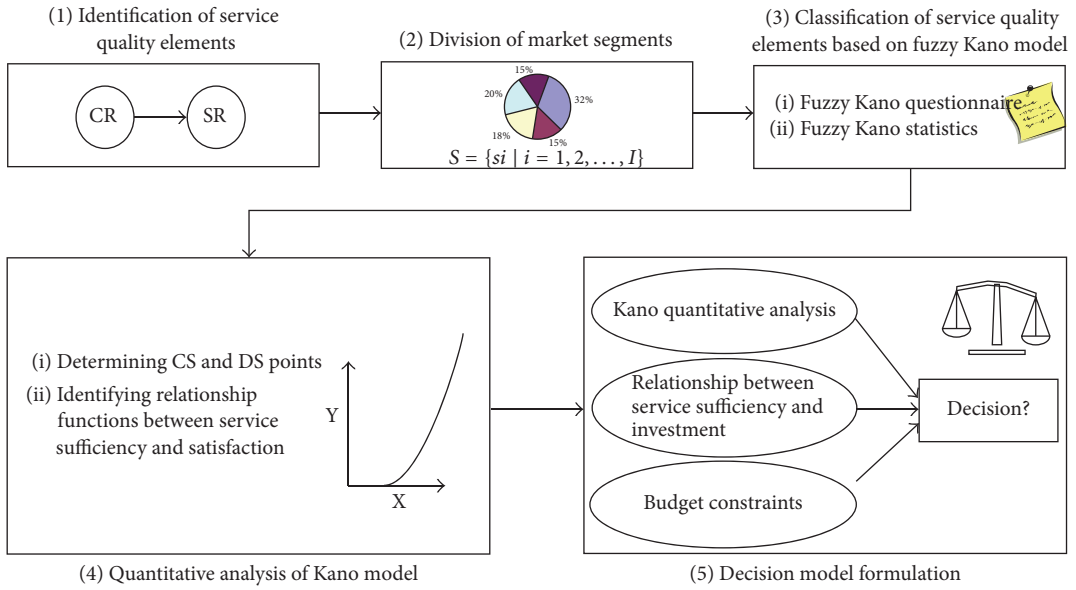

Figure 2: The proposed research framework.

fuzzy linguistics and fuzzy inference, and it is successfully used in fuzzy decision-making [55]. Thus, some scholars suggested incorporating the fuzzy set theory into Kano model to accommodate linguistic properties of subjective and vague human perception [22–24]. The fuzzy Kano model has been found capable of mimicking a realistic cognition process in practice. An evaluator's multiple feelings can be expressed by the possibility degrees in the fuzzy Kano model. In this study, we are inclined to use fuzzy Kano model to elicit customers' perception and gain classification results of service quality elements [55].

3.4. Quantitative Analysis of the Kano Model. After the classification results based on the fuzzy Kano model are obtained, the quantitative analysis is conducted as the literature of Wang and Ji (2010) [21].

Based on the findings of service quality elements classification, it is possible to calculate two values, namely, customer satisfaction (CS) and customer dissatisfaction (DS) [19]:

$$\begin{aligned} \mathrm{CS}_i &= \frac{f_A + f_O}{f_A + f_O + f_M + f_I}, \\ \mathrm{DS}_i &= \frac{f_O + f_M}{f_A + f_O + f_M + f_I}. \end{aligned} \tag{1}$$

Let f_A denote the number of attractive quality elements, f_O the number of one-dimensional quality elements, f_M the number of must-be quality elements, and f_I the number of indifferent quality elements.

Consequently, the two points define the customer satisfaction if a quality element can be fully fulfilled or completely nonfulfilled. These points can be plotted as $(1, \mathrm{CS}_i)$ and $(0, -\mathrm{DS}_i)$ [21]. The relationship function between customer satisfaction and service quality element fulfillment can be identified given the category of the quality element. The relationship function can be expressed as $S = f(x, a, b)$, where S denotes the customer satisfaction, x denotes the fulfillment level, and a and b are adjustment parameters for the Kano categories of service quality elements. For one-dimensional quality elements, the function is $S = a_1 x + b_1$, and the shape of the linear curve must pass the CS and DS points. Then we can get $a_1 = \mathrm{CS}_i - \mathrm{DS}_i$ and $b_1 = \mathrm{DS}_i$. Therefore, the function for one-dimensional quality elements is

$$S_{oi} = (\mathrm{CS}_i - \mathrm{DS}_i)\, x_{oi} + \mathrm{DS}_i. \tag{2}$$

For attractive quality elements, the function can be seen to be exponential; $S = a_2 e^x + b_2$. Substituting $(1, \mathrm{CS}_i)$ and $(0, -\mathrm{DS}_i)$ into the equation, we can get $a_2 = (\mathrm{CS}_i - \mathrm{DS}_i)/(e - 1)$ and $b_2 = -(\mathrm{CS}_i - e\mathrm{DS}_i)/(e - 1)$. The function for attractive quality elements is therefore

$$S_{ai} = \frac{\mathrm{CS}_i - \mathrm{DS}_i}{e - 1} e^{x_{ai}} - \frac{\mathrm{CS}_i - e\mathrm{DS}_i}{e - 1}. \tag{3}$$

Using the similar approach, for must-be quality elements, the function is modified to be $S = -a_3 e^{-x} + b_3$, and we can acquire $a_3 = e(\mathrm{CS}_i - \mathrm{DS}_i)/(e - 1)$ and $b_3 = (e\mathrm{CS}_i - \mathrm{DS}_i)/(e - 1)$. Then the function for must-be quality elements is

$$S_{mi} = -\frac{e\,(\mathrm{CS}_i - \mathrm{DS}_i)}{e - 1} e^{-x_{mi}} + \frac{e\mathrm{CS}_i - \mathrm{DS}_i}{e - 1}. \tag{4}$$

3.5. Decision Model Formulation. In this stage, a decision model for maximizing service quality under budget constraints is developed based on the quantitative Kano model. Different service quality element categories have different influence on satisfaction. Fulfilling customer expectations of service quality to a great extent does not necessarily guarantee a higher customer satisfaction. Sufficient provision will lead to increased costs. It is a very important task to seek for an efficient way to leverage the customer satisfaction and

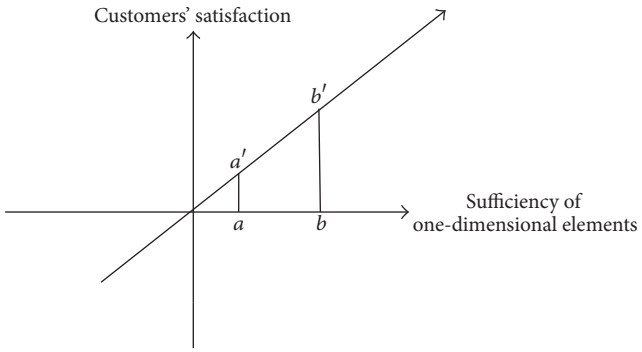

Figure 3: Sufficiency of one-dimensional elements and customers' satisfaction.

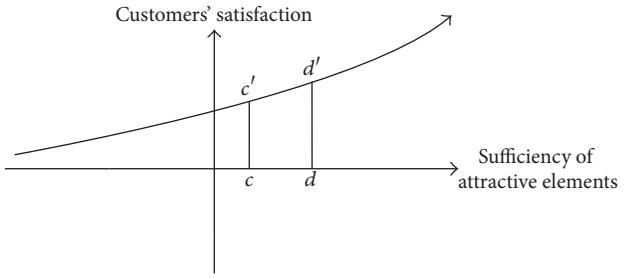

Figure 4: Sufficiency of attractive elements and customers' satisfaction.

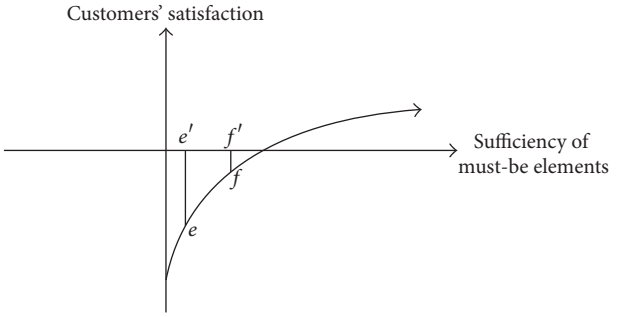

Figure 5: Sufficiency of must-be elements and customers' satisfaction.

cost constraints. This will be done using a service quality maximization model, and its construction will be shown in the following section. Firstly, the relationships between sufficiencies of different service quality elements categories and customer satisfactions are discussed.

(i) One-Dimensional Quality Elements. Figure 3 shows the function for one-dimensional quality elements identified in Section 3.4. When the sufficiency is provided by x_{oi} from level a to b resulting from one unit of monetary investment, the increased satisfaction, A_o, is the area A_o surrounded by points a, b, a', and b', and it can be computed as

$$A_o = \int_a^b \left[\left(\mathrm{CS}_i - \mathrm{DS}_i\right) x_{oi} + \mathrm{DS}_i\right] dx_{oi}. \tag{5}$$

When an enterprise provides n one-dimensional service quality elements and if the sufficiency provided by each x_{oi} increases from a_i to b_i, then TA_o, the level of satisfaction increased by n one-dimensional elements, can be expressed as

$$TA_o = \sum_{i=1}^{n} A_{oi} = \sum_{i=1}^{n} \int_{a_i}^{b_i} \left[\left(\mathrm{CS}_i - \mathrm{DS}_i\right) x_{oi} + \mathrm{DS}_i\right] dx_{oi}, \quad i = 1, 2, \ldots, n. \tag{6}$$

For simplicity, assuming that $a_1 = a_2 = \cdots = a_n = a, b_1 = b_2 = \cdots = b_n = b$, the total increased customer satisfaction TA_o provided by n one-dimensional elements can be computed as

$$TA_o = \sum_{i=1}^{n} \int_{a}^{b} \left[\left(\mathrm{CS}_i - \mathrm{DS}_i\right) x_{oi} + \mathrm{DS}_i\right] dx_{oi}. \tag{7}$$

(ii) Attractive Quality Elements. Figure 4 shows the example of an attractive quality element. The relationship function is $S_{ai} = ((\mathrm{CS}_i - \mathrm{DS}_i)/(e-1))e^{x_{ai}} - (\mathrm{CS}_i - e\mathrm{DS}_i)/(e-1)$, and when the sufficiency is provided by x_{ai} from level c to d resulting from one unit of monetary investment, the increased satisfaction A_a surrounded by points c, d, c', and d' can be computed as

$$A_a = \int_c^d \left(\frac{\mathrm{CS}_i - \mathrm{DS}_i}{e-1} e^{x_{ai}} - \frac{\mathrm{CS}_i - e\mathrm{DS}_i}{e-1}\right) dx_{ai}. \tag{8}$$

If n attractive quality elements provided, with the sufficiency of each x_{ai}, increase from c_i to d_i, the increased satisfaction TA_a can be expressed as

$$TA_a = \sum_{i=1}^{n} A_a = \sum_{i=1}^{n} \int_{c_i}^{d_i} \left(\frac{\mathrm{CS}_i - \mathrm{DS}_i}{e-1} e^{x_{ai}} - \frac{\mathrm{CS}_i - e\mathrm{DS}_i}{e-1}\right) dx_{ai}, \quad i = 1, 2, \ldots, n. \tag{9}$$

For the ease of manifestation, assuming that $c_1 = c_2 = \cdots = c_n = c, d_1 = d_2 = \cdots = d_n = d$, the total increased satisfaction TA_a can be simplified as

$$TA_a = \sum_{i=1}^{n} \int_{c}^{d} \left(\frac{\mathrm{CS}_i - \mathrm{DS}_i}{e-1} e^{x_{ai}} - \frac{\mathrm{CS}_i - e\mathrm{DS}_i}{e-1}\right) dx_{ai}. \tag{10}$$

(iii) Must-Be Quality Elements. As Figure 5 shows, the relationship function for must-be quality element is $S_{mi} = -(e(\mathrm{CS}_i - \mathrm{DS}_i)/(e-1))e^{-x_{mi}} + (e\mathrm{CS}_i - \mathrm{DS}_i)/(e-1)$, and when the sufficiency is provided by x_{mi} from level e to f resulting from one unit of monetary investment, the decreased dissatisfaction A_m surrounded by points e, f, e', and f' is computed as

$$A_m = \int_e^f \left(-\frac{e\left(\mathrm{CS}_i - \mathrm{DS}_i\right)}{e-1} e^{-x_{mi}} + \frac{e\mathrm{CS}_i - \mathrm{DS}_i}{e-1}\right) dx_{mi}. \tag{11}$$

If n must-be quality elements provided, with the sufficiency provided by each x_{mi}, increase from e_i to f_i, then the decreased dissatisfaction TA_m can be expressed as

$$TA_m = \sum_{i=1}^{n} A_m = \sum_{i=1}^{n} \int_{e_i}^{f_i} \left(-\frac{e\left(\mathrm{CS}_i - \mathrm{DS}_i\right)}{e-1} e^{-x_{mi}} + \frac{e\mathrm{CS}_i - \mathrm{DS}_i}{e-1} \right) dx_{mi}, \quad i = 1, 2, \ldots, n. \tag{12}$$

Assuming that $e_1 = e_2 = \cdots = e_n = e$, $f_1 = f_2 = \cdots = f_n = f$, the total decreased dissatisfaction TA_m is simplified as

$$TA_m = \sum_{i=1}^{n} \int_{e}^{f} \left(-\frac{e\left(\mathrm{CS}_i - \mathrm{DS}_i\right)}{e-1} e^{-x_{mi}} + \frac{e\mathrm{CS}_i - \mathrm{DS}_i}{e-1} \right) dx_{mi}. \tag{13}$$

The equations above now can be applied to improve the machinery service quality. There are many factors that can be related to the machinery service quality, and some fall into must-be elements, and others are one-dimensional or attractive quality elements. Moreover, the increased satisfaction resulting from investment on must-be, one-dimensional, and attractive quality elements is certainly different. Thus, the problem is how to properly allocate the budget to service quality elements in order to maximize the overall customer satisfaction. At this point the following model can be proposed:

$$\begin{aligned} M\text{: max} \quad & C_o\left(TA_o\right) + C_a\left(TA_a\right) + C_m\left(TA_m\right) \\ \text{s.t.} \quad & C_o + C_a + C_m \le B \\ & 0 \le C_o \le B \\ & 0 \le C_a \le B \\ & 0 \le C_m \le B \\ & C_o = k_1\left(b - a\right) \\ & C_a = k_2\left(d - c\right) \\ & C_m = k_3\left(f - e\right) \\ & 0 \le a \le b \le D \le 1 \\ & 0 \le c \le d \le E \le 1 \\ & 0 \le e \le f \le F \le 1, \end{aligned} \tag{14}$$

where C_o, C_a, and C_m denote the individual budget allocated to one-dimensional, attractive, and must-be quality elements and these are the decision variables. B is the total budget to improve the overall service quality. When budgeted, C_o can be increased from a to b with D being the upper limit. With the same principles, C_a can be increased from c to d with E being the upper limit, and C_m can be increased from e to f with F being the upper limit. The coefficients of k_1, k_2, and k_3 stand for the relationship between budget allocated and the level of quality improvement. The nonlinear mathematical model can be solved by optimization software Lingo, and the details will be shown in the following illustrative example.

4. An Empirical Study

To demonstrate the performance of the proposed method, an empirical study in Xuzhou Construction Machinery Group Co., Ltd. (XCMG), is given in this section. XCMG is the largest construction machinery company in China. Its products cover road machineries, crane trucks, heavy-duty road rollers, and so on, which include 75 series and 330 varieties. The product sales network of XCMG covers more than 170 countries and regions, and the annual export value has exceeded $1.6 Billion USD. But in recent years with the scale enlargement of markets and the implementation of the "Going Global" strategy, XCMG is facing much greater variety and uncertainty in customer requirement. XCMG now needs to explore the appropriate strategy on the service quality management to gain competitive advantage. Since 2011, XCMG launched the project of "Hanfeng Program" to establish a control system for service quality improvement. And the decision method proposed in this paper is implied in the program.

4.1. Service Quality Elements Identification in XCMG. Based on the SERVQUAL model, several experts in XCMG and some users are investigated by the team members, and twelve service quality elements and benefits provided for customers in XCMG are extracted in Table 2.

4.2. Data Collection and Analysis. According to the twelve service quality elements, the fuzzy Kano questionnaire is designed, which is divided into two parts: in the first part, there is some demographic information of respondents such as organization characters (state-owned business, private business, foreign-funded enterprise, or joint venture enterprise) and types of customers (general customers, key accounts, or strategic customers). In the second part, the questionnaire focuses on a set of 12 items of service quality elements, and the form of each item is presented with both functional and dysfunctional forms, but, unlike traditional Kano model using binary data, the fuzzy Kano model questionnaire allows respondents to express their multiple feelings by the possibility degrees among multiple items. Additional information on the fuzzy Kano questionnaire can be found in the literature [55].

The fuzzy Kano questionnaire is distributed randomly face-to-face by the employees from marketing department and after-sale service support department and team members in the program. The first step is to provide respondents with a brief introduction of Kano model, and then customers are asked to give multiple answers of the pair questions about service quality elements. From September 15 to December 15, 2012, 250 copies of the questionnaire have been issued and 196 completed copies are retrieved. This is a reasonable response rate of 78.4%. The sample demographic characteristics are shown in Table 3.

Table 2: Service quality elements and benefits provided for customers in XCMG.

Service quality elements	Description and specification	Benefits provided
SQ_1	Fulfill service commitments, maintenance service in PLC	Reliability, safety
SQ_2	Quick response to requirements and complaints	Speediness
SQ_3	Consultation and solutions customization	Empathy, added value
SQ_4	Repair and maintenance service covers widely	Safety, assurance, and reliability
SQ_5	Machinery vehicles status monitoring and warning, long range information transmission, and diagnosis	Safety, convenience
SQ_6	Value-added service	Added value, empathy
SQ_7	Network and online service	Convenience, speediness
SQ_8	Used machinery vehicles business	Convenience, empathy
SQ_9	High quality service staffs' professional and technical abilities	Pleasure, assurance
SQ_{10}	Compensation for delaying	Reliability, safety
SQ_{11}	Proactive services provided regularly and periodically	Convenience, reliability
SQ_{12}	Customer participation in service process	Added value, empathy

Table 3: Demographic characteristics of respondents.

Demographic characteristics	Number	Percentage (%)
Organization characters		
State-owned business	54	27.55%
Private business	43	21.94%
Foreign-funded enterprise	47	23.98%
Joint venture enterprise	52	26.53%
Types of customers		
General customers	79	40.31%
Key accounts	65	33.16%
Strategic customers	52	26.53%

4.3. Service Quality Elements Classification. Based on fuzzy Kano survey and statistical analysis, the classification results of service quality elements in XCMG are given from the preliminary qualitative results by the author [55], as is shown in Table 4.

4.4. Decision Results. According to results of service quality elements classification, the service quality elements, SQ_{11} (proactive services provided regularly and periodically) and SQ_{12} (customer participation in service process), are classified as indifferent quality elements. They are not included in the further analysis due to the low impact on customer satisfaction. At this point the proposed quantitative analysis in Section 3 is applied. Firstly, the values of CS and DS are computed for each service quality element as shown in Table 5. Based on the classification results in Table 4, the values of a and b are calculated to determine the function for each service quality element. Accordingly, all the relationship functions of three category quality elements are estimated in Table 5.

Given the data of cost for each service quality element drawn from investigation in XCMG, as is shown in Table 6, the total budget for service quality improvement is ¥150,000.

Assuming $k_1 = 150$, $k_2 = 300$, $k_3 = 100$, $a = 0.55$, $c = 0.55$, $e = 0.55$, and $D = 0.9$, $E = 0.8$ and $F = 1$. Then the model becomes

$$
\begin{aligned}
M\text{: max} \quad & C_o\left(TA_o\right) + C_a\left(TA_a\right) + C_m\left(TA_m\right) \\
\text{s.t.} \quad & C_o + C_a + C_m \le 150 \\
& 0 \le C_o \le 150 \\
& 0 \le C_a \le 150 \\
& 0 \le C_m \le 150 \\
& C_o = 150\,(b - 0.55) \\
& C_a = 300\,(d - 0.55) \\
& C_m = 100\,(f - 0.55) \\
& 0.55 \le b \le 0.9 \\
& 0.55 \le d \le 0.8 \\
& 0.55 \le f \le 1.0 \\
& TA_o = 2.015b^2 - 2.03b + 0.507 \\
& TA_a = 1.32e^d - 2.25d - 1.0504 \\
& TA_m = 8.88e^{-f} + 5.51f - 8.1538.
\end{aligned}
\tag{15}
$$

The nonlinear programming model is solved by Lingo 11.0, and the results are obtained as $C_o = 52.5$, $C_a = 52.5$, and $C_m = 45$; $TA_o = 0.31$, $TA_a = 0.04$, and $TA_m = 0.62$; and the overall customer satisfaction is 46.72. It appears that XCMG should allocate ¥52,500 to improve the one-dimensional quality elements, with the level of service quality being improved from 0.55 to 0.9. ¥52,500 of the budget should be allocated for the attractive quality elements, with the level of service quality being improved from 0.55 to 0.725. And ¥45,000 should be allocated for the must-be quality elements, and it will improve the level of service quality from 0.55 to 1.

To examine the appropriateness of the results, three different parameter values of coefficients k_i are applied in the model for a sensitivity analysis. Due to the fact that the categories of service quality elements are the most effective factors on resource utilization, the sensitivity analysis focuses mainly on the coefficients k_i. Table 7 shows the results of the sensitivity analysis.

The results in Table 7 show that the coefficients k_i have some effect on the decision-making results. In the three

Table 4: Service quality elements classification results from Kano model.

Service quality elements (number)	Traditional Kano model					Fuzzy Kano model				
	M	A	I	O	Category	M	A	I	O	Category
SQ_1	88	32	25	51	M	106	38	18	44	M
SQ_2	78	45	23	50	M	98	42	20	51	M
SQ_3	45	38	20	93	O	51	43	25	99	O
SQ_4	89	51	11	45	M	95	56	15	37	M
SQ_5	40	82	24	50	A	46	88	27	53	A
SQ_6	45	90	16	45	A	49	92	18	48	A
SQ_7	84	39	26	47	M	95	52	24	38	M
SQ_8	37	90	21	48	A	39	48	19	92	O
SQ_9	49	90	19	38	A	54	46	24	95	O
SQ_{10}	51	80	15	50	A	84	56	13	47	M
SQ_{11}	38	59	80	19	I	43	64	86	25	I
SQ_{12}	55	47	73	21	I	56	48	78	22	I

Table 5: Quantitative results of service quality elements based on Kano model.

Number	CS	DS	CS point	DS point	a	b	$f(x)$	$S = af(x) + b$
SQ_1	0.40	−0.73	(1, 0.4)	(0, −0.73)	1.78	1.05	e^{-x}	$S = -1.78e^{-x} + 1.05$
SQ_2	0.44	−0.71	(1, 0.44)	(0, −0.71)	1.81	1.11	e^{-x}	$S = -1.81e^{-x} + 1.11$
SQ_3	0.65	−0.69	(1, 0.65)	(0, −0.69)	1.34	−0.69	x	$S = 1.34x - 0.69$
SQ_4	0.46	−0.65	(1, 0.46)	(0, −0.65)	1.75	1.10	e^{-x}	$S = -1.75e^{-x} + 1.10$
SQ_5	0.66	−0.46	(1, 0.66)	(0, −0.46)	0.65	−1.12	e^{x}	$S = 0.65e^{x} - 1.12$
SQ_6	0.68	−0.47	(1, 0.68)	(0, −0.47)	0.67	−1.13	e^{x}	$S = 0.67e^{x} - 1.13$
SQ_7	0.43	−0.64	(1, 0.43)	(0, −0.64)	1.69	1.05	e^{-x}	$S = -1.69e^{-x} + 1.05$
SQ_8	0.71	−0.66	(1, 0.71)	(0, −0.66)	1.37	−0.66	x	$S = 1.37x - 0.66$
SQ_9	0.64	−0.68	(1, 0.64)	(0, −0.68)	1.32	−0.68	x	$S = 1.32x - 0.68$
SQ_{10}	0.52	−0.66	(1, 0.52)	(0, −0.66)	1.85	1.20	e^{-x}	$S = -1.85e^{-x} + 1.2$

Table 6: Cost for each service quality element.

Service quality elements (number)	Description and specification	Costs (¥1000)
SQ_1	Fulfill service commitments, maintenance service in PLC	4800
SQ_2	Quick response to requirements and complaints	295
SQ_3	Consultation and solutions customization	400
SQ_4	Repair and maintenance service covers widely	4300
SQ_5	Machinery vehicles status monitoring and warning, long range information transmission, and diagnosis	360
SQ_6	Value-added service	200
SQ_7	Network and online service	170
SQ_8	Used machinery vehicles business	215
SQ_9	High quality service staffs' professional and technical abilities	310
SQ_{10}	Compensation for delaying	460

conditions, the must-be quality elements will first achieve their targets (always $f = 1$), and they must be allocated to the budget to be fully fulfilled, while the one-dimensional and attractive quality elements are quite different. The performance of must-be quality elements has the priority in service quality improvement. With a limited budget (¥150,000) it can only be guaranteed that the must-be and one-dimensional quality elements achieve their goals, while the attractive quality elements cannot be assured.

4.5. Suggestions. From the results, it appears that XCMG should firstly invest in must-be quality elements to assure an entirely fulfilled system with limited resources. Specifically, XCMG will establish a service standard system to fulfill service commitments, provide the maintenance service in a product's life cycle, and assure these quality elements to a high level. XCMG must guarantee a quick response to service requirements and complaints from customers, and this can be done through the use of both a Customer Relationship Management (CRM) system and Mobile Internet Technology (MIT). The service quality element "repair and maintenance service covers widely" will be improved in a large scale

Table 7: Solutions with different parameter values of k_i.

Number	k_1	k_2	k_3	C_o	C_a	C_m	TA_o	TA_a	TA_m	b	d	f	max CS
1	150	300	100	52.5	52.5	45	0.31	0.04	0.62	0.9	0.73	**1**	46.72
2	100	150	300	0	15	135	$3.75 * 10^{-5}$	0.02	0.62	0.55	0.65	**1**	**84.34**
3	300	100	150	102.73	0.02	47.25	0.30	0	0.62	0.89	0.55	**1**	60.28

with the business expansion. Meanwhile, "the network and online service" needs also to be investigated within the company, as poor service quality for this element leads to strong dissatisfaction. If the must-be quality elements are not fulfilled, it would be essential to provide compensation to customers that place complaints.

The one-dimensional elements of "consultation and solutions customization," "used machinery vehicles business," and "high quality service staffs' professional and technical abilities" should also be improved to a high level to maximize customer satisfaction for XCMG. Considering customers' heterogeneities, service customization and service specialization will be the general trend in the future. The service quality is significantly related with service staffs, and XCMG must make sure that there are a group of service employees with high levels of professional and technical abilities. In addition to the focus on must-be and one-dimensional elements, it is wise to seek for some effective ways to improve the attractive quality elements, if there is potential for additional monetary investment.

The decision method proposed is also practical and functional for other enterprises to improve service quality. Firstly, it is critical to better identify and understand service quality elements from customers' perspective. Secondly, it is necessary to account for the budget constraints in the decision-making of service quality improvement. Thirdly, with the limited budget, to maximize the overall customer satisfaction, the must-be quality elements must be allocated to the budget to be fully fulfilled and to achieve the targets.

5. Conclusions

Service quality has become one of the sources for competitive advantage, especially for some machinery industries transforming into product-service system providers. And more importantly, service quality is the crucial determinant of customer satisfaction and customer loyalty. This integrated framework, proposed for maximizing machinery industry service quality under budget constraints, involves service quality elements identification and classification, quantitative analysis of Kano model, and decision model formulation. It provides a guidance principle of "origin from customers, application for customers" for enterprises to manage service quality in the customers-dominated logic era. As Wang and Ji (2010) [21] stated before, it is important to provide a way for quantitative Kano model to be integrated with other mathematical models for optimizing customer-focused product or service design.

The contributions of this research can be summarized as follows. First, the decision method proposed provides a systematic and quantitative solution for improving service quality in machinery manufacturers to balance customer satisfaction and service costs. Second, the integrated framework gives a practical roadmap for enterprises to improve service quality with limited budgets, and it involves several key processes: service quality elements identification, classification, and service quality improvement decision-making. Finally, the results provide empirical evidence that must-be quality elements have higher priorities in budget allocation for quality improvement, compared with one-dimensional and attractive quality elements, under the limited budgets.

Yet, there are some limitations in this paper. Firstly, in the nonlinear programming model (14), the coefficients parameters which related the budgets to the level of quality improvement should be discussed further, using a large amount of historical data in the future. Secondly, in the empirical research, the perceptions varieties in classification of service quality elements from different customer segments are not considered. And it is significant for the enterprises to make decisions with different customer orientation. Finally, more empirical studies on the decision method should be conducted to test the applicability.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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Research Article

Modified Bat Algorithm Based on Lévy Flight and Opposition Based Learning

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Bat Algorithm (BA) is a swarm intelligence algorithm which has been intensively applied to solve academic and real life optimization problems. However, due to the lack of good balance between exploration and exploitation, BA sometimes fails at finding global optimum and is easily trapped into local optima. In order to overcome the premature problem and improve the local searching ability of Bat Algorithm for optimization problems, we propose an improved BA called OBMLBA. In the proposed algorithm, a modified search equation with more useful information from the search experiences is introduced to generate a candidate solution, and Lévy Flight random walk is incorporated with BA in order to avoid being trapped into local optima. Furthermore, the concept of opposition based learning (OBL) is embedded to BA to enhance the diversity and convergence capability. To evaluate the performance of the proposed approach, 16 benchmark functions have been employed. The results obtained by the experiments demonstrate the effectiveness and efficiency of OBMLBA for global optimization problems. Comparisons with some other BA variants and other state-of-the-art algorithms have shown the proposed approach significantly improves the performance of BA. Performances of the proposed algorithm on large scale optimization problems and real world optimization problems are not discussed in the paper, and it will be studied in the future work.

1. Introduction

With the development of natural science and technology, a large number of complicated optimization problems arise in a variety of fields, such as engineering, manufacturing, information technology, and economic management. These real world problems usually have an objective function with lots of decision variables and constrains, appearing with discontinuous, nonconvex features [1]. Optimization methods are always needed to obtain the optimal solution of these problems.

Optimization algorithms proposed by researchers can be categorized into two groups: deterministic algorithms and stochastic algorithms. Deterministic algorithms usually need the information of gradient. They are effective for problems with one global optimum, while they might be invalid for problems with several local optima or problems with gradient information unavailable. Compared with deterministic algorithms, stochastic algorithms require only the information of the objective function [2]. They have been successfully used in many optimization problems characterized as nondifferentiable and nonconvex.

Swarm intelligence algorithms, regarded as a subset of stochastic algorithms, have been widely used to solve optimization problems during the past decades. They are inspired by the collective behavior of swarms in nature. Researchers have observed such behaviors of animals, plants, or humans, analyzed the driving force behind the phenomena, and then proposed various types of algorithms. For example, Genetic Algorithm (GA) [3] and Differential Evolution (DE) [4] were generalized by inspiration of the biological evolution and natural selection. Particle Swarm Optimization (PSO) [5] was proposed by simulating the social and cognitive behavior of fish or bird swarms. Ant Colony Algorithm (ACO) [6]

and Artificial Bee Colony (ABC) [7] were introduced by the foraging behavior of ants and bees. Cat Swarm Algorithm (CSO) [8], Cuckoo Search Algorithm (CS) [9], and Bat Algorithm (BA) [10] were also proposed by inspiration from the intelligence features in behaviors or organisms of swarms.

Bat Algorithm, proposed by Yang in 2010, is a swarm intelligence algorithm inspired by the echolocation behavior of bats. Echolocation is a type of sonar which is used by bats to detect prey, hunt, and avoid obstacles. With the help of echolocation, not only can the bats be able to detect the distance of the prey, but also they can identify the shape, position, and angle of the prey [10]. Compared with other existing swarm intelligence algorithms, BA has many advantages such as less control parameters, excellent global optimization ability, and implementation simplicity, which have shown excellent performances in some classes of optimization problems. Due to its simplicity, convergence speed, and population feature, it has been intensively used to solve academic and real life problems, like multiobjective optimization [11], engineering optimization [12], cluster analysis [13], scheduling problems [14], structure optimization [15], image processing [16], manufacturing designing [17], and various other problems.

It has been shown that BA is an excellent and powerful algorithm for global optimization problems, discrete optimization problems, and constrained optimization problems. However, due to the lack of good balance between exploration and exploitation in basic BA, the algorithm sometimes fails at finding global optimum and is easily trapped into local optima. Much efforts have been made to improve the performance of BA. These improvements or modifications can be divided into two categories.

Introduction of New Search Mechanisms for Generating Candidate Solutions. Inspired by DE, Xie et al. [18] presented a modified approach DLBA with a new solution update mechanism combining the concept of differential operator and Lévy Flight trajectory. Li and Zhou [19] embedded the complex value encoding mechanism into Bat Algorithm to improve the diversity and convergence performance. Gandomi and Yang [20] introduced chaotic maps into the population initialization and position update equation and proposed a modified algorithm. Bahmani-Firouzi and Azizipanah-Abarghooee [21] proposed four improved velocity update equations in order to achieve a better balance between the exploration and exploitation. Jaddi et al. [22] divided the swarm population into two subpopulation groups with each group designed to generate solutions according to different equations, respectively. Yilmaz and Küçüksille [23] defined two modification structures of the velocity equation inspired by PSO and then hybridized the modified BA with Invasive Weed Optimization algorithm. The velocity equations used information of the best-so-far solution and the neighborhood solutions, which can effectively enhance the search ability of BA.

Hybridization of BA with Other Operators. For example, Khan and Sahai [24] proposed a hybrid approach involving PSO, HS, and SA for generating new solutions. Wang and Guo [25] introduced a mutation operator into BA using SA. He et al. [26] developed a hybrid BA which combines SA and Gauss distribution. Sadeghi et al. [27] developed a hybrid BA with local search based on PSO. Lin et al. [28] developed a chaotic BA with Lévy Flights and parameters estimated by chaotic maps. Meng et al. [29] incorporated the bats' habitat selection and their self-adaptive compensation for Doppler effect in echoes into the basic BA and proposed a new self-adaptive modified algorithm NBA.

The study is not limited to the above two aspects and more work can be seen in [30–34] and so on.

As technology and science develop dramatically fast, more and more complicated optimization problems need to be solved by advanced numerical methods. As an important heuristic optimization algorithm, researches on how to improve the convergence accuracy and efficiency of BA are of great significance to improve the heuristic optimization theory and solve the real world optimization problems.

Exploration and exploitation are two critical characteristics in the updating process of an algorithm. Exploration is the ability of the algorithm to find the global optimum solutions in different areas of the search space, while exploitation refers to the capability of the algorithm to find better solutions with previous experience. Researches in the literature show that, for a swarm intelligence algorithm, the exploration capability should be employed first so as to search in the whole space, while the exploitation capability should be considered later by improving the quantity of the solution in the local search process [23].

To achieve a better balance between exploration and exploitation behavior of BA, it is highly required to modify the global search approach to explore the search region and develop a local search method to exploit in the nonvisited regions. Accordingly, modifications of the search equation and local search strategies for BA are studied in the research. A modified algorithm called OBMLBA is proposed in this study. The main difference between OBMLBA and other BAs is the interaction behavior between bats. In the proposed approach, the bat explores the search space with the help of the best-so-far solution and the neighborhood solutions by using echolocation, which can well balance the exploration and exploitation. The new population P is generated by using a new modified position update equation with frequency f defined by sinusoidal function. Lévy Flight random walk is used to exploit the local search space whereas opposition based learning is used to introduce opposition based solutions in population OP. Individuals of P and OP are merged together, and the best N individuals are used as a new population for the next generation. The proposed method has been tested on 16 benchmark functions. Comparison with variants of BA and other state-of-the-art algorithms demonstrates the effectiveness and superiority of OBMLBA in solving optimization problems.

The paper is organized as follows. After the introduction, the basic concept of BA is introduced in Section 2. The proposed OBMLBA is presented in Section 3. Section 4 evaluates the performance of the proposed algorithm by comparing results with other algorithms. Finally, conclusions and future work are discussed in Section 5.

(1) Input the parameters.
(2) Set iter = 1. Initialize the position and velocity of each individual in the population.
(3) Evaluate the objective function and related parameter values of each individual.
(4) **While** iter ≤ iter_max **do**
(5) Generate new solutions using Eq. (2)~Eq. (4).
(6) **if** rand$(0, 1) > r_i$
(7) Generate a new local solution around the selected solution x^* using Eq. (5).
(8) **end if**
(9) **if** rand$(0, 1) < A_i$ and $f(x^i_{\text{new}}) < f(x_i)$
(10) update the solution, loudness and pulse emission rate by Eq. (6).
(11) **end if**
(12) **end while**
(13) Output the individual with the smallest objective function value in the population.

Algorithm 1: Basic Bat Algorithm.

2. Basic Bat Algorithm

The optimization problems considered in this paper are single-objective, unconstrained continuous problems to be minimized.

Bat Algorithm is a heuristic algorithm proposed by Yang in 2010. It is based on the echolocation capability of micro bats guiding them on their foraging behavior. In BA, the position of a bat represents a possible solution of the given optimization problem. The position of the food source found by the ith bat can be expressed as $x_i = (x_{i,1}, x_{i,2}, \ldots, x_{i,D})$. The fitness of x_i corresponds to the quality of the position the bat locates in.

2.1. Initiation. At the beginning, bats do not know the location of food sources. They generate a randomly distributed population P of N solutions, where N denotes the number of bats in the population. Each solution can be produced within the search space as follows:

$$x_{ij} = x_{\min} + \text{rand}\,(0, 1)\left(x_{\max} - x_{\min}\right), \tag{1}$$

where $i = 1, 2, \ldots, N$, $j = 1, 2, \ldots, D$. $x_{\max}$ and $x_{\min}$ denote the upper and lower bounds of the solution in dimension j, respectively. rand$(0, 1)$ is a uniformly distributed value generated in the range of $[0, 1]$.

2.2. Generation of New Solutions. Bats modify the solution based on the information of the current location and the best source food location. Bats navigate by adjusting their flying directions using their own and other swarm members' best experience to find the optimum of the problem.

At this stage, for each food source position x_i, a new position was formulated as follows:

$$f_i = f_{\min} + \beta\left(f_{\max} - f_{\min}\right), \tag{2}$$

$$v_i^t = v_i^{t-1} + \left(x_i^t - x^*\right) f_i, \tag{3}$$

$$x_i^t = x_i^{t-1} + v_i^t, \tag{4}$$

where i represents each bat in the population, $i = 1, 2, \ldots, N$, and t represents the tth iteration. x_i^t and v_i^t are the position and velocity components of the ith bat in the population at the tth iteration. f_i denotes the pulse frequency that affects the velocity of the ith bat. $f_{\max}$ and $f_{\min}$ represent the maximum and minimum of f_i. β is a random number between $[0, 1]$. x^* is the best position found by the whole population.

2.3. Local Search. Once the new solutions are generated, the local search is invoked by bats' random walk. If the pulse emission rate r of the ith bat is smaller than a random number, select x^i_{old} from the population and generate a new position x^i_{new} as follows:

$$x^i_{\text{new}} = x^i_{\text{old}} + \varepsilon A^t, \tag{5}$$

where x^i_{old} represents a solution chosen in current population by some mechanism and ε is a random vector drawn from a uniform distribution. A^t is the average loudness of all bats at the time step t.

2.4. Solutions, Loudness, and Pulse Emission Rate Updating. If a random number is bigger than the loudness A^t and $f(x^i_{\text{new}}) < f(x_i)$, accept the new solution x^i_{new}. At the same time, the loudness A^t is decreased while its pulse emission r_i is increased as follows:

$$\begin{aligned} A_i^{t+1} &= \alpha A_i^t, \\ r_i^{t+1} &= r_i^0\left(1 - e^{\gamma t}\right), \end{aligned} \tag{6}$$

where α and γ are constants. The initial loudness A^0 and initial pulse emission rate r^0 are randomly generated numbers in the range of $[1, 2]$ and $[0, 1]$, respectively.

The pseudocode of Bat Algorithm is presented in Algorithm 1.

3. Enhanced Bat Algorithm

3.1. Location Update Equation Based on DE. Yilmaz and Küçüksille [23] pointed that the update equations of velocity in basic BA provide local search only with the guidance of the best-so-far solution, which makes the BA easily entrapped

into a local minimum. In order to improve the search ability, they proposed a modified equation:

$$v_i^t = \omega v_i^{t-1} + \left(x_i^t - x^*\right) f_i \zeta_1 + \left(x_i^t - x_k^t\right) f_i \zeta_2, \quad (7)$$

$$\zeta_1 + \zeta_2 = 1, \quad (8)$$

$$\zeta_1 = 1 + \left(\zeta_{\text{init}} - 1\right) \frac{\left(\text{iter}_{\max} - \text{iter}\right)^n}{\left(\text{iter}_{\max}\right)^n}, \quad (9)$$

where x_k^t is a solution randomly chosen from the population and ζ_1 and ζ_2 are learning factors ranging from 0 to 1. ζ_{init} is the initial value of ζ_1. $\text{iter}_{\max}$ is the maximal number of iterations. iter is the number of iterations, and n is a nonlinear index.

The second term in the modified search equation is a factor affecting the velocity of the solution with guidance of the best solution x^*, which emphasizes exploitation. The third term is another factor that affects the velocity with help of randomly selected solution x_k^t which emphasizes exploration. Effects of the best solution and the kth solution are adjusted by changing the value of ζ_1. Experiments results indicate that the modified algorithm can outperform BA in most test functions.

Xie et al. [18] proposed an improved BA based on Differential Evolution operator. The position updating equations were defined as follows:

$$x_i^{t+1} = x_{\text{best}}^t + f_{1i}\left(x_{r1}^t - x_{r2}^t\right) + f_{2i}\left(x_{r3}^t - x_{r4}^t\right), \quad (10)$$

where x_{best}^t is the global best location in current population. x_{ri}^t $(i = 1, 2, 3, 4)$ is a randomly chosen solution in the population. f_{1i} and f_{2i} are defined as follows:

$$f_{1i}^t = \left(\left(f_{1,\min} - f_{1,\max}\right)\frac{t}{n_t} + f_{1,\max}\right)\beta_1, \quad (11)$$

$$f_{2i}^t = \left(\left(f_{2,\min} - f_{2,\max}\right)\frac{t}{n_t} + f_{2,\max}\right)\beta_2, \quad (12)$$

where $f_{1,\max}$ and $f_{1,\min}$ are minimum and maximum frequency values of f_{1i}, while $f_{2,\max}$ and $f_{2,\min}$ are minimum and maximum frequency values of f_{2i}. n_t is a fixed parameter. t is the number of iterations. $\beta \in [0, 1]$ is a random vector drawing a uniform distribution. The modified algorithm has shown a better performance than classical BA.

Inspired by Yilmaz and Zhou's methods, we propose a modified location updating equation:

$$x_i^{t+1} = x_i^t + f_{1i}\left(x_{\text{best}}^t - x_{r1}^t\right) + f_{2i}\left(x_{r2}^t - x_{r3}^t\right), \quad (13)$$

where x_{ri}^t $(i = 1, 2, 3)$ are individuals randomly selected from the population. f_{1i} and f_{2i} are frequencies.

As in mutation operation of DE, the frequency f is an important parameter that affects the convergence performance of the algorithm. The value of f changes according to the predefined formula. In basic BA and DLBA, f is defined in (2), (11), and (12), respectively. Here we use a sinusoidal formulation [35] permitting certain flexibility in changing the direction of f. The frequencies f_{1i} and f_{2i} are defined as follows:

$$f_{1i} = \frac{1}{2}\left(\sin\left(2\pi * \omega * t\right) * \frac{\text{iter}}{\text{iter}_{\max}} + 1\right), \quad (14)$$

$$f_{2i} = \frac{1}{2}\left(\sin\left(2\pi * \omega * t\right) * \frac{\text{iter}}{\text{iter}_{\max}} + 1\right), \quad (15)$$

where ω represents frequency of the sinusoidal function.

3.2. Local Search Based on Lévy Flight. Lévy Flight, which is based on the flight behavior of animals and insects, has been variously studied in literatures [36]. It is defined as a kind of non-Gauss stochastic process with a random walk whose step sizes are based on Lévy stable distribution.

There are lots of versions of Lévy distribution. Mantegna Algorithm [37] has been tested to be the most efficient method to generate Lévy distribution values. It has been adopted in many evolution algorithms in order to escape from local minimum.

When generating a new solution x_i' for the ith solution x_i by performing Lévy Flight, the new candidate x_i' is defined as follows:

$$x_i' = x_i + \alpha \oplus \text{Levy}\left(\lambda\right), \quad (16)$$

where α is a random step size parameter, λ is a Lévy Flight distribution parameter, and $\oplus$ denotes entry wise multiplication.

In Mantegna Algorithm, the step size s can be defined as follows:

$$s = \alpha \oplus \text{Levy}\left(\lambda\right) \sim 0.01\frac{u}{|v|^{1/\beta}}\left(x_j - x_{\text{best}}\right), \quad (17)$$

where u and v are obtained from normal distribution; that is,

$$u \sim N\left(0, \sigma_u^2\right), \quad v \sim N\left(0, \sigma_v^2\right) \quad (18)$$

with

$$\sigma_u = \left\{\frac{\Gamma\left(1+\beta\right)\sin\left(\pi\beta/2\right)}{\beta\Gamma\left[\left(1+\beta\right)/2\right]2^{(\beta-1)/2}}\right\}^{1/\beta}, \quad \sigma_v = 1, \quad (19)$$

$$\Gamma\left(z\right) = \int t^{z-1}e^{-z}dz. \quad (20)$$

The pseudocode of Lévy Flight Search is shown in Algorithm 2.

3.3. Opposition Based Learning. Opposition based learning was proposed by Rahnamayan et al. [38] in 2005. It has been successfully used in machine learning and evolutionary computing [39]. For an optimization problem, if the candidate solutions are near the global optima, it is easy to find the ideal solutions with fast convergence speed. But if the candidate

(1) Input the optimization function $f(x)$ and β.
(2) Select the individual x_i which is chosen to be modified by Lévy Flight.
(3) Compute σ_u using Eq. (19).
(4) Compute step size s using Eq. (17) and Eq. (18).
(5) Generate a new candidate solution x_i' using Eq. (16).
(6) Calculate $f(x')$.
(7) **if** $f(x_i') < f(x_i)$
(8) $x_i = x_i'$.
(9) **end if**

Algorithm 2: Pseudocode of Lévy Flight Search.

(1) Input original population P, population size SN, the dimension of solution D, optimization function $f(x)$.
(2) Generate opposite population OP as follows:
(3) **for** $i = 1 : SN$
(4) **for** $j = 1 : D$
(5) $x_{ij} = a_i + b_i - x_{ij}$;
(6) **end for**
(7) **end for**
(8) Merge the original population P and opposite population OP together.
(9) Calculate the fitness of population $\{P, \text{OP}\}$.
(10) Choose the top half of population $\{P, \text{OP}\}$ as the current population.

Algorithm 3: Opposition based optimization.

solutions are far away from the global optima, it will take more computational efforts to get the required solutions. The concept of OBL is to consider the candidate solutions and their opposite counterpart solutions simultaneously in an optimization algorithm. Then the greedy selection is applied between them according to their objective function values. With the help of OBL, the probability of finding global optima is increased.

In basic OBL, let $x = (x_1, x_2, \ldots, x_D)$ be a D-dimensional solution in the search space, with component variables $x_i \in [a_i, b_i]$. Then the opposite point $\widetilde{x} = (\widetilde{x}_1, \widetilde{x}_2, \ldots, \widetilde{x}_D)$ is defined by its coordinates $\widetilde{x}_1, \widetilde{x}_2, \ldots, \widetilde{x}_D$, where

$$\widetilde{x}_i = a_i + b_i - x_i, \quad i = 1, 2, \ldots, D. \tag{21}$$

OBL can be used not only to initialize the population initialization, but also to improve the population diversity during the evolutionary process. Once the opposite population generated, it is combined with the original population for selection. Individuals with fitness ranking in the top half of all candidate solutions will be selected as the current population. The pseudocode of OBL is given in Algorithm 3.

3.4. Proposed Modified Bat Algorithm. Based on the basic BA and the above considerations, we propose a modified method, called OBMLBA. It is clear that local search with Lévy Flight can improve the ability of exploitation. Incorporating with OBL strategy can enhance the population diversity. Inspired by DLBA, the new location update equation takes advantage of the information of both the global best solution and randomly chosen solution near the candidate solution. So the modified BA can get a good balance between the exploration and exploitation. The main steps of the algorithm are summarized in Algorithm 4.

4. Experimental Results and Discussion

In order to evaluate the performance of the proposed algorithm, we select 16 standard benchmark functions to investigate the efficiency of the proposed approach. These functions are presented in Table 1. The function set comprises unimodal functions and multimodal functions, which can be used to test the convergence speed and local premature convergence problem, respectively. F_1~F_5 are continuous unimodal functions. F_7 is a discontinuous step function. F_9 is a noisy quartic function. F_{10}~F_{16} are multimodal functions with high dimension. These functions are categorized into low-dimension, middle-dimension, and high-dimension functions according to $D = 15$, 30, and 60, respectively.

Related parameters of the basic BA, DLBA, and OBMLBA are presented in Table 2. The maximum number of iterations is set to be 500, 1000, and 2000 in case of $D = 15$, 30, and 60.

Experiments have been carried out on the test functions with different dimensions. The computational results are summarized in Tables 3–5 in terms of the mean error and standard deviation of the function error values. In addition, some convergence characteristics graphs are shown in Figure 1.

(1) Input the parameters.
(2) Set iter = 1. Initialize the position and velocity of each individual in the population.
(3) Evaluate the objective function and related parameter values of each individual.
(4) **While** iter ≤ iter_max **do**
(5) Apply Lévy Flight Local Search strategy using Algorithm 2.
(6) Generate new solutions using Eq. (13).
(7) **if** rand(0, 1) > r_i
(8) Apply the Opposition based learning using Algorithm 3.
(9) Generate a new local solution around the selected solution x^* using Eq. (5).
(10) **end if**
(11) **if** rand(0, 1) < A_i and $f(x^i_{\text{new}}) < f(x_i)$
(12) update the solution, loudness and pulse emission rate.
(13) **end if**
(14) **end while**
(15) Output the individual with the smallest objective function value in the population.

Algorithm 4: Pseudocode of OBMLBA.

Table 1: Benchmark problems.

Fun	Name	Scope	$f_{\min}$
F_1	Sphere	[−100, 100]	0
F_2	Elliptic	[−100, 100]	0
F_3	SumSquare	[−10, 10]	0
F_4	SumPower	[−1, 1]	0
F_5	Schwefel2.22	[−10, 10]	0
F_6	Schwefel2.21	[−100, 100]	0
F_7	Step	[−100, 100]	0
F_8	Exponential	[−1.28, 1.28]	0
F_9	Quartic	[−1.28, 1.28]	0
F_{10}	Rosenbrock	[−5, 10]	0
F_{11}	Rastrigin	[−5.12, 5.12]	0
F_{12}	Griewank	[−600, 600]	0
F_{13}	Ackley	[−32, 32]	0
F_{14}	Alpine	[−10, 10]	0
F_{15}	Levy	[−10, 10]	0
F_{16}	Weierstrass	[−0.5, 0.5]	0

Table 2: Parameters setting.

Parameters	BA	DLBA	OBMLBA
Population size N		40	
Run time		20	
Loudness		0.95	
Pulse emission		0.85	
Factors updating A and γ		0.9	
Minimum of frequency f_{min}		0	
Maximum of frequency $f_{\max}$		1	
Factors updating frequency	—	—	0.3

As seen from Tables 3–5, OBMLBA can get the global optimal on f_1~f_4, f_7, f_8, and f_{11}~f_{13} with $D = 15$, 30, and 60. On f_6 and f_{14}, the precision of solutions obtained by OBMLBA is smaller than the order of $1E-90$ and the order for $1E-100$, respectively. Results indicate that OBMLBA can get solutions extremely close to the global optimal values on most of the functions.

Solutions obtained by BAs are compared with results obtained by MLBA and OBMLBA. As shown in Tables 3–5, OBMLBA performs significantly better than basic BA, LBA, and DLBA on f_1~f_6, f_{14}, and f_{15}. All algorithms except for basic BA and LBA perform well on f_7, f_8, f_{11}~f_{13}, and f_{16}. OBMLBA is comparable to DLBA and MLBA on functions f_9 and f_{10}.

Compared with MLBA, OBMLBA provides better performance on functions f_1~f_6, f_{14}, and f_{15}. For f_9, f_{10}, and f_{15}, results obtained by MLBA and OBMLBA are quite close to each other. Both MLBA and OBMLBA get the global optimum of f_7, f_8, f_{11}~f_{13}, and f_{16}.

From the convergence characteristic graphs, it can be obviously observed that OBMLBA is the fastest algorithm in all the considered BAs. MLBA is slower than OBMLBA but faster than DLBA, LBA, and basic BA. OBMLBA exhibits the best accuracy and achieves the fastest convergence speed. The results indeed indicate the advantage of the modified position update equation and OBL strategy.

On the whole, algorithms proposed in this study such as MLBA and OBMLBA work better than other BAs considered. And OBMLBA is more effective than MLBA.

In Table 6, OBMLBA is compared with some state-of-the-art algorithms, such as ABC, PSO, OCABC, CLPSO, and OLPSO-G. Results of these algorithms are all derived directly from their corresponding literatures [40]. Results show that OBMLBA has outperformed other methods on 6 of 7 functions. OBMLBA performs worse than ABC and OCABC only on Rosenbrock function.

According to the analyses above, it can be clearly observed that OBMLBA provides outstanding performance with fast convergence speed and high convergence accuracy on most of the test functions.

Table 3: Results of comparisons of BAs on 15-dimension benchmark functions.

Fun	BA		LBA		DLBA		MLBA		OBMLBA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F_1	$1.19E+04$	$1.84E+03$	$2.60E+03$	$2.53E+03$	$4.45E-54$	$1.39E-53$	$2.30E-69$	$7.07E-69$	**3.6601E − 204**	**0**
F_2	$7.05E+07$	$3.04E+07$	$1.89E+07$	$1.93E+07$	$1.02E-42$	$4.54E-42$	$3.96E-67$	$1.25E-66$	**3.4713E − 202**	**0**
F_3	$8.10E+02$	$1.39E+02$	$1.32E+02$	$2.25E+02$	$3.77E-52$	$1.69E-51$	$8.10E-66$	$2.56E-65$	**6.2179E − 202**	**0**
F_4	$2.59E-02$	$1.50E-02$	$1.64E-03$	$2.35E-03$	$5.22E-90$	$2.27E-89$	$4.57E-126$	$1.2069E-125$	**1.12E − 305**	**0**
F_5	$4.08E+01$	$7.24E+00$	$1.08E+01$	$1.43E+01$	$3.73E-28$	$1.45E-27$	$1.75E-33$	$5.52E-33$	**1.17E − 104**	**5.2441E − 104**
F_6	$5.01E+01$	$3.16E+00$	$1.47E+01$	$1.46E+01$	$3.04E-27$	$1.00E-26$	$2.50E-35$	$7.85E-35$	**6.68E − 95**	**2.98692E − 94**
F_7	$1.11E+04$	$2.13E+03$	$1.36E+03$	$2.16E+03$	**0**	**0**	**0**	**0**	**0**	**0**
F_8	$1.52E+00$	$4.43E-01$	$1.26E-01$	$2.62E-01$	**0**	**0**	**0**	**0**	**0**	**0**
F_9	$2.65E+00$	$1.13E+00$	$1.34E-01$	$2.70E-01$	$4.79E-04$	$4.31E-04$	$3.99E-04$	$2.82E-04$	**1.19E − 04**	**1.00E − 04**
F_{10}	$5.89E+04$	$2.02E+04$	$6.03E+02$	$1.34E+03$	$1.35E+01$	$2.10E-01$	**1.29E + 01**	**3.71E − 01**	$1.30E+01$	$3.40E-01$
F_{11}	$1.31E+02$	$8.16E+00$	$7.81E+01$	$4.48E+01$	**0**	**0**	**0**	**0**	**0**	**0**
F_{12}	$1.06E+02$	$2.24E+01$	$1.66E+01$	$2.27E+01$	**0**	**0**	**0**	**0**	**0**	**0**
F_{13}	$1.83E+01$	$4.88E-01$	$1.07E+01$	$5.65E+00$	**0**	**0**	**0**	**0**	**0**	**0**
F_{14}	$1.42E+01$	$1.04E+00$	$5.29E+00$	$5.26E+00$	$1.82E-27$	$7.92E-27$	$5.67E-35$	$1.79E-34$	**8.91E − 106**	**3.6823E − 105**
F_{15}	$1.52E+02$	$1.13E+01$	$2.73E+01$	$1.76E+01$	$7.47E-01$	$3.00E-01$	**2.78E − 01**	**2.74E − 01**	$4.83E-01$	$5.26E-01$
F_{16}	$1.68E+01$	$1.60E+00$	$9.87E+00$	$5.23E+00$	**0**	**0**	**0**	**0**	**0**	**0**

Table 4: Results of comparisons of BAs on 30-dimension benchmark functions.

Fun	BA		LBA		DLBA		MLBA		OBMLBA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F_1	$4.05E+04$	$2.80E+03$	$3.80E+03$	$6.80E+03$	$3.73E-49$	$1.67E-48$	$1.80E-117$	$5.68E-117$	**0**	**0**
F_2	$5.30E+08$	$1.15E+08$	$9.54E+07$	$8.35E+07$	$2.96E-50$	$1.25E-49$	$3.20E-117$	$1.01E-116$	**0**	**0**
F_3	$5.15E+03$	$7.97E+02$	$7.29E+02$	$1.21E+03$	$9.80E-48$	$4.38E-47$	$2.72E-123$	$6.51E-123$	**0**	**0**
F_4	$7.53E-02$	$2.97E-02$	$5.80E-03$	$1.39E-02$	$1.74E-85$	$7.78E-85$	$1.76E-198$	0	**0**	**0**
F_5	$2.33E+05$	$4.28E+05$	$7.58E+01$	$1.78E+02$	$9.72E-26$	$4.33E-25$	$5.12E-60$	$1.62E-59$	**6.80E − 210**	**0**
F_6	$6.83E+01$	$3.50E+00$	$1.76E+01$	$1.96E+01$	$5.42E-30$	$1.11E-29$	$2.63E-55$	$8.33E-55$	**1.40E − 205**	**0**
F_7	$3.71E+04$	$4.26E+03$	$5.69E+03$	$8.14E+03$	**0**	**0**	**0**	**0**	**0**	**0**
F_8	$2.39E+01$	$6.19E+00$	$1.23E+00$	$2.62E+00$	**0**	**0**	**0**	**0**	**0**	**0**
F_9	$4.02E+01$	$6.91E+00$	$2.25E+00$	$5.19E+00$	$2.85E-04$	$2.83E-04$	$2.30E-04$	$1.20E-04$	**6.25E − 05**	**4.21E − 05**
F_{10}	$3.85E+05$	$6.51E+04$	$2.59E+04$	$6.15E+04$	$2.87E+01$	$6.22E-02$	$2.83E+01$	$2.16E-01$	**2.82E + 01**	**2.48E − 01**
F_{11}	$3.37E+02$	$1.57E+01$	$2.13E+02$	$7.34E+01$	**0**	**0**	**0**	**0**	**0**	**0**
F_{12}	$3.61E+02$	$3.39E+01$	$3.74E+01$	$5.97E+01$	**0**	**0**	**0**	**0**	**0**	**0**
F_{13}	$1.96E+01$	$2.71E-01$	$6.56E+00$	$5.25E+00$	**0**	**0**	**0**	**0**	**0**	**0**
F_{14}	$4.26E+01$	$2.74E+00$	$1.55E+01$	$1.42E+01$	$1.26E-27$	$5.56E-27$	$2.91E-60$	$9.10E-60$	**3.30E − 215**	**0**
F_{15}	$5.00E+02$	$8.97E+01$	$6.96E+01$	$6.04E+01$	$9.01E+00$	$3.07E+00$	$5.78E+00$	$2.82E+00$	**5.17E + 00**	**2.40E + 00**
F_{16}	$4.13E+01$	$1.17E+00$	$1.61E+01$	$1.38E+01$	**0**	**0**	**0**	**0**	**0**	**0**

Table 5: Results of comparisons of BAs on 60-dimension benchmark functions.

Fun	BA		LBA		DLBA		MLBA		OBMLBA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
F_1	$1.03E+05$	$9.37E+03$	$3.53E+03$	$8.71E+03$	$4.54E-49$	$2.02E-48$	$1.21E-219$	$0.00E+00$	**0**	**0**
F_2	$2.38E+09$	$2.51E+08$	$6.07E+08$	$8.73E+08$	$9.65E-43$	$4.32E-42$	$1.61E-217$	$0.00E+00$	**0**	**0**
F_3	$2.95E+04$	$3.02E+03$	$1.24E+03$	$2.03E+03$	$2.13E-54$	$5.66E-54$	$8.19E-224$	$0.00E+00$	**0**	**0**
F_4	$1.47E-01$	$4.25E-02$	$2.79E-03$	$6.28E-03$	$2.05E-88$	$9.18E-88$	$0.00E+00$	0	**0**	**0**
F_5	$1.00E+10$	$0.00E+00$	$2.76E+01$	$3.04E+01$	$4.78E-24$	$2.14E-23$	$4.78E-112$	$1.51E-111$	**0**	**0**
F_6	$8.21E+01$	$2.42E+00$	$1.15E+01$	$1.53E+01$	$3.21E-28$	$7.05E-28$	$1.95E-107$	$6.13E-107$	**0**	**0**
F_7	$9.83E+04$	$8.72E+03$	$1.17E+04$	$2.18E+04$	0	0	0	0	**0**	**0**
F_8	$5.46E+03$	$4.31E+03$	$2.74E+01$	$8.12E+01$	0	0	0	0	**0**	**0**
F_9	$2.76E+02$	$4.78E+01$	$2.55E+00$	$7.94E+00$	$2.70E-04$	$2.54E-04$	**1.56E − 04**	**7.75E − 05**	$2.82E-05$	$2.77E-05$
F_{10}	$1.77E+06$	$3.90E+05$	$1.80E+04$	$3.47E+04$	$5.86E+01$	$7.21E-02$	$5.83E+01$	$1.52E-01$	**1.01E + 01**	**8.32E − 01**
F_{11}	$7.73E+02$	$2.79E+01$	$3.09E+02$	$2.70E+02$	**0**	**0**	**0**	**0**	**0**	**0**
F_{12}	$9.03E+02$	$1.21E+02$	$3.72E+01$	$6.01E+01$	**0**	**0**	**0**	**0**	**0**	**0**
F_{13}	$2.03E+01$	$6.71E-02$	$6.36E+00$	$5.72E+00$	**0**	**0**	**0**	**0**	**0**	**0**
F_{14}	$1.08E+02$	$4.42E+00$	$5.06E+01$	$3.91E+01$	$5.26E-29$	$2.20E-28$	$6.46E-104$	$2.04E-103$	**0**	**0**
F_{15}	$1.49E+03$	$1.92E+02$	$2.74E+02$	$2.97E+02$	$4.14E+01$	$9.79E+00$	$2.42E+01$	$6.61E+00$	**4.58E − 02**	**6.53E − 02**
F_{16}	$9.30E+01$	$1.52E+00$	$3.35E+01$	$2.68E+01$	**0**	**0**	**0**	**0**	**0**	**0**

Table 6: Comparisons of the state-of-the-art algorithms on 30-dimension benchmark functions.

Fun	ABC		PSO		OCABC		CLPSO		OLPSO-G		OBMLBA	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Sphere	$6.80E-14$	$8.74E-14$	$3.34E-14$	$5.39E-14$	$4.05E-41$	$6.97E-41$	$1.58E-12$	$7.70E-13$	$4.12E-54$	$6.34E-54$	**0**	**0**
Schweel222	$4.58E-08$	$1.98E-08$	$1.70E-10$	$1.39E-10$	$9.13E-22$	$7.98E-22$	$2.51E-08$	$5.84E-09$	$9.85E-30$	$1.01E-29$	**6.80E − 210**	**0**
Step	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Rosenbrock	**1.68E − 01**	**2.04E − 01**	$2.80E+01$	$2.17E+01$	$4.39E-01$	$7.26E-01$	$1.13E+01$	$8.50E+01$	$2.15E+01$	$2.99E+01$	$2.82E+01$	$2.48E-01$
Rastrigin	$2.90E-07$	$8.64E-07$	$3.57E+01$	$6.89E+00$	**0**	**0**	$9.09E-05$	$1.25E-04$	$1.07E+00$	$9.92E-01$	**0**	**0**
Griewank	$1.69E-05$	$4.88E-05$	$1.53E-03$	$4.32E-03$	**0**	**0**	$9.02E-09$	$8.57E-09$	$4.83E-03$	$8.63E-03$	**0**	**0**
Ackley	$1.09E-06$	$5.96E-07$	$8.20E-08$	$6.73E-08$	$3.83E-15$	$9.83E-16$	$3.66E-07$	$7.57E-08$	$7.98E-15$	$2.03E-15$	**0**	**0**

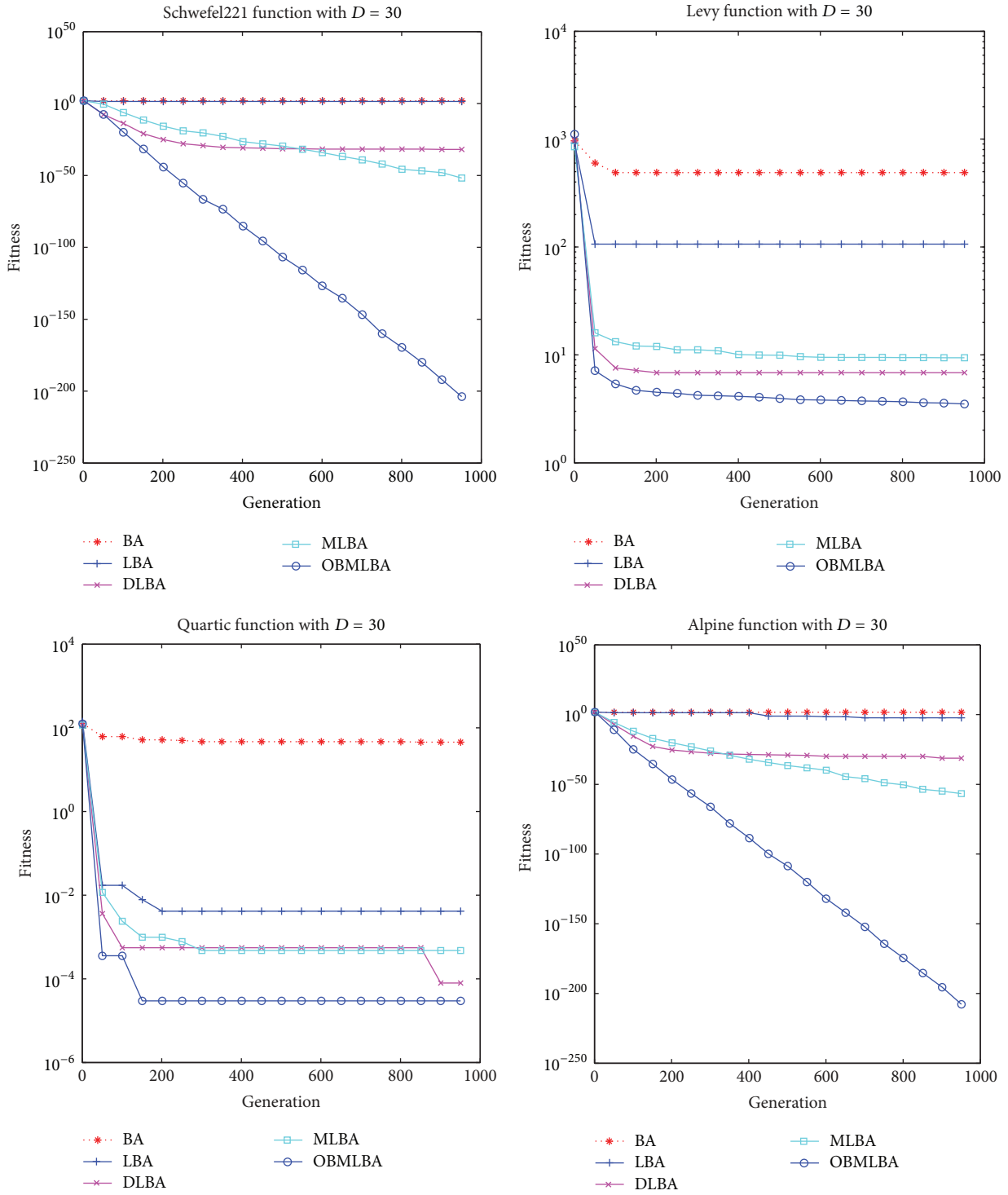

Figure 1: Convergence performance of BAs on the test functions.

5. Conclusions

Bat Algorithm, a metaheuristic algorithm proposed recently, has been successfully used to solve different types of optimization problems. However, it also has some inefficiency on exploration and exploitation capabilities.

In this study, a new variant of Bat Algorithm called OBMLBA is presented. The exploration and exploitation abilities of BA are balanced and enhanced in the search process by combining the information of the best-so-far solution and the neighborhood solutions into the search equations. At the same time, the proposed equation uses sinusoidal function

to define the bat pulse frequency f, allowing flexibility in changing the direction of f. Furthermore, Lévy Flight random walk is taken into consideration to escape from local optima. The concept of opposition based learning is introduced to the algorithm to improve the diversity and convergence capability. The proposed approach has been successfully used on 16 benchmark functions. Results and comparisons with the basic BA, DLBA, and other state-of-the-art algorithms show that OBMLBA has outperformed considered approaches in most of the functions. However, these experiments are just small scale optimization problems. The performance of the proposed algorithm on large scale optimization problems and real world optimization problems should be deeply investigated. The future study of this method may focus on investigating the mathematical foundations and applications of the proposed algorithm.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Volatility Spillovers in Capesize Forward Freight Agreement Markets

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This paper is to investigate spillovers in the Capesize forward freight agreements (FFAs) markets before and after the global financial crisis. The paper chooses four Capesize voyage routes FFAs (C3, C4, C5, and C7), two time-charter routes FFAs (BCIT/C average, BPI T/C average), and spot rates as research subjects, covering the periods 3 January 2006 to 24 December 2015. This paper applies Volatility Spillover Multivariate Stochastic Volatility (VS-MSV) model to analyze volatility spillover effects and estimates the parameters via software of Bayesian inference using Gibbs Sampling (BUGS), the deviance information criterion (DIC) used for goodness-of-fit model. The results suggest that there are volatility spillover effects in certain Capesize FFAs routes, and the effects from spot rates to FFAs take place before crisis, yet they are bilateral after crisis. With the development of shipping markets, the correlations between FFAs and spot rate are enhanced, and it seems that the effects depend on market information and traders' behavior. So practitioners could make decisions according to the spillovers.

1. Introduction

Cross-market information transmission is a research area that received a lot of attention from both academia and practitioners [1]. With the development of shipping derivative markets, the relationships between related markets are closer. After global financial crisis, the financial risks transmission enhances relationships among different shipping derivative markets. Unlike the variable's first moment relationship reflected in the price spillover effect, the volatility spillover effect reflects the variable's second moment relationship, in which market volatility is influenced not only by its own early stage but also by volatility coming from other markets [2]. The volatility spillover effect exists widely in different shipping derivative markets. It is an important aspect of volatility in shipping industry.

As a main component of shipping derivatives, forward freight agreements (FFAs) are over-the-counter products made on a principal-to-principal basis at the beginning, and now they are traded both over the counter and through exchange. Freight derivatives provide a means of hedging exposure to freight market risk through the trading of specified time-charter and voyage rates for forward positions.

According to the efficient market hypothesis, the FFAs price should be unbiased estimator of the spot price, which is the underlying asset. Yet it is not always true in FFAs markets. So the relationship between FFAs and spot rates is paid attention [3–8], especially the spillover effects. Chung and Weon [9] employ two versions of bivariate asymmetric mixed normal GARCH models to capture the skewness and kurtosis detected in both the conditional and unconditional return distributions of dry-bulk freight rates. Li et al. [10] investigate spillover effects and dynamic correlations between shipping spot and derivatives markets under the multivariate generalized autoregressive conditional heteroscedasticity framework and find that spillovers in returns are unilateral from one-month FFA to spot markets, while they are bilateral between one-month and two-month FFA markets. Sogiakas and Karathanassis [11] examine volatility spillovers between spot and derivatives markets without accounting for possible disequilibria in the long term relationship that could potentially result in spurious spillover effects and provide evidence of

a time-varying spillover effect from derivatives to spot markets. Alexandridis et al. [12] investigate the economic spillovers between time-charter rates, freight futures, and freight options prices in the dry-bulk shipping industry; the results indicate the existence of significant information transmission in both returns and volatilities between the three related markets. Shi et al. [13] use a univariate generalized ARCH model to capture the volatility characteristics of freight derivative returns and apply time-varying copula models to describe the nonlinear dependence between returns of spot and freight derivatives. As we have known, since global financial crisis, in order to avoid credit risk, over 90% of FFAs trading volume is through clearing house after global economic crisis [14]. That is to say the crisis changed the manner of settlement for FFAs; however, whether it influences relationship between FFAs and spot rate should be studied furthermore.

With the development of research, the relationships are paid attention between FFAs and commodity markets. Chou [15] applies the vector autoregressive moving-average model (VARMA) and uses variables from one-year FFAs and the global oil index to analyze the relationships between the two instruments. Chou et al. [16] attempt to discover the dynamic relationship between crude oil prices and the global steel price index and find that the crude oil price moves prior to movements in the global steel price index. Kavussanos et al. (2014) investigate economic spillovers between the freight and commodity derivatives markets, and the investigation of various types of commodities transported under different types of freight contracts reveals that in most cases new information appears first in the returns and volatilities of the commodities futures markets, before it is spilled over into the freight derivatives markets. As is well known, bulk shipping is the tramp shipping, and one ship could run on different routes. So there may be relationships among FFAs prices on different voyage routes. At the same time, different types of ships could run on the same route; therefore, FFAs price of different types of ships could be related, such as Capesize and Panamax. In this paper, the spillover effects are investigated among voyage routes FFAs prices and between time-charter routes FFAs, comparing before and after global financial crisis, in order to analyze volatility characters of FFAs markets.

Now the main model studying volatility in shipping markets is generalized autoregressive conditional heteroscedasticity (GARCH) model [4, 17, 18]. With the research going, extended models are applied. Alizadeh and Nomikos [19] investigate the relationship between the dynamics of the term structure and time-varying volatility of shipping freight rates, using augmented EGARCH models, and find support for the argument that the volatility of freight rates is related to the shape of the term structure of the freight market. Alizadeh (2013) investigates the price volatility and trading volume relationship in the forward freight agreement (FFA) market for dry-bulk ships over the period 2007–2011, using an exponential GARCH model, and finds that FFA price changes have a positive impact on trading volume. Alizadeh et al. [20] examine the effectiveness of alternative hedging methods, including a bivariate Markov regime switching GARCH model, in hedging tanker freight rates, and find evidence supporting the argument that the tanker freight market is characterized by different regimes. Tsouknidis [21] examines the existence of dynamic volatility spillovers within and between the dry-bulk and tanker freight markets by employing the multivariate DCC-GARCH model, and results reveal the existence of large time-varying volatility spillovers across shipping freight markets, which are more intense during and after the global financial crisis. As another volatility models, the Stochastic Volatility models are used widely for researching volatility of financial markets [22–25]. Some literatures show that the SV models are better than GARCH models for analyzing volatility in financial markets [26, 27]. Yet there are few literatures using the SV models to investigate volatility in shipping. The paper applies the extended SV model to investigate spillover effects in FFAs markets.

In addition, some researches focus on investigating Panamax FFAs market, while Capesize FFAs market is more important for China. The reason is that China is the biggest iron importer, and the volume of imports is over 70% of the world, which is mainly transported by Capesize ships. So this paper investigates the volatility spillover effects among Capesize FFAs markets, Panamax FFAs markets, and spot markets, comparing with different Capesize routes and different periods, before and after global economic crisis, in order to get some findings to help shipping operation and management. This will also be helpful in trade using FFAs which could manage shipping risk and improve management level. The remainder of this paper is structured as follows. Section 2 presents the theoretical framework and Volatility Spillover Multivariate Stochastic Volatility (VS-MSV) model. Section 3 is the numerical statistics analysis. Section 4 contains empirical results. Section 5 concludes the paper.

2. Methodology

2.1. VS-MSV Model. Harvery et al. [28] and So et al. [29] put forward Multivariate Stochastic Volatility (MSV) model on the basis of Stochastic Volatility (SV) model.

The basic SV model is as follows:

$$\begin{aligned} y_t &= \varepsilon_t \exp\left(\frac{h_t}{2}\right), \quad t = 1, 2, \ldots, T, \ \varepsilon_t \sim \text{i.i.N}(0, 1), \\ h_t &= \alpha + \beta\left(h_{t-1} - \alpha\right) + \eta_t, \quad \eta_t \sim \text{i.i.N}(0, 1). \end{aligned} \tag{1}$$

y_t indicates FFAs return of one route at time t and h_t is a stationary AR(1) process. ε_t is a martingale difference, which follows the normal distribution, ε_t and η_t are contemporaneously dependent, and α and β are parameters to be estimated. T is the sample size.

Similar to basic model, MSV model is as follows:

$$\begin{aligned} y_{it} &= \xi_{it} \exp\left(\frac{h_{it}}{2}\right), \quad i = 1, 2, \ldots, m, \ t = 1, 2, \ldots, T, \\ h_{it} &= \alpha_i + \varphi_i\left(h_{i,t-1} - \alpha_i\right) + \eta_{it}, \quad i = 1, 2, \ldots, m. \end{aligned} \tag{2}$$

y_{it} indicates FFAs returns of different routes at time t. Random error vectors ξ_{it} and η_{it} are multivariate normal vectors,

and the mean values are both zero. α_i and φ_i are parameters to be estimated.

MSV model indicates the impact of $h_{i,t-1}$ on h_{it} without considering the impact of other h_{it} ($j \neq t$, $j \neq t-1$), so it could not analyze the volatility spillover effects with SV or MSV. With the development of economic globalization, the volatility spillover effect becomes common. In order to study the effect, parameter vector φ_i is extended to matrix Φ [30].

$$\Phi = \begin{pmatrix} \varphi_{11} & \cdots & \varphi_{1m} \\ \cdots & \cdots & \cdots \\ \varphi_{m1} & \cdots & \varphi_{mm} \end{pmatrix}, \tag{3}$$

where φ_{ij} indicates the impact of $h_{j,t-1}$ on $h_{i,t}$ ($i \neq j$). So the Volatility Spillover Multivariate Stochastic Volatility (VS-MSV) model is as follows:

$$\begin{aligned} y_{it} &= \Omega\xi_{it}, \quad \xi_{it} \sim N\left(0, \Sigma_\xi\right), \\ \Omega &= \operatorname{diag}\left(\exp\left(\frac{h_{1t}}{2}\right), \exp\left(\frac{h_{2t}}{2}\right), \ldots, \exp\left(\frac{h_{mt}}{2}\right)\right), \\ h_{it} &= \alpha_i + \Phi\left(h_{i,t-1} - \alpha_i\right) + \eta_{it}, \quad \eta_{it} \sim N\left(0, \Sigma_\eta\right). \end{aligned} \tag{4}$$

Here, y_{it} is returns of FFAs for kinds i at time t. ξ_{it} and η_{it} are the random variables and independent, identically distributed with normal distribution, and the mean values are both zero, yet the variances are Σ_ξ and Σ_η, respectively. h_{it} are the volatilities, α_i and Φ are parameters, and Φ are persistence parameters.

The covariance matrix Σ_ξ is given by

$$\begin{aligned} \Sigma_\xi = E\left(\xi_t \xi_t^T\right) &= E\begin{pmatrix} \xi_{1t}^2 & \cdots & \xi_{1t}\xi_{mt} \\ \cdots & \cdots & \cdots \\ \xi_{mt}\xi_{1t} & \cdots & \xi_{mt}^2 \end{pmatrix} \\ &= \begin{pmatrix} 1 & \cdots & \rho_{1m} \\ \cdots & \cdots & \cdots \\ \rho_{1m} & \cdots & 1 \end{pmatrix}. \end{aligned} \tag{5}$$

Random error vector h_{it} is the multivariate normal vector, $\eta_{it} \sim N(0, \Sigma_\eta)$. Σ_η is given by

$$\Sigma_\eta = \begin{pmatrix} E\left(\eta_{1t}^2\right) & \cdots & E\left(\eta_{1t}\eta_{mt}\right) \\ \cdots & \cdots & \cdots \\ E\left(\eta_{mt}\eta_{1t}\right) & \cdots & E\left(\eta_{mt}^2\right) \end{pmatrix}. \tag{6}$$

2.2. Parameter Estimation and Test. The Bayesian analysis and Markov Chain Monte Carlo (MCMC) method are used to estimate parameters. Finally, it gets the Bayesian estimation results. In VS-MSV model, unknown parameters include α_i and Φ (including $2m + m^2$ unknown parameters).

Firstly, suppose that the parameters of vector θ are independent, and $p(\cdot)$ indicates probability density function of random stochastic variable. Joint prior density of unknown parameters and unobservable variables is as follows:

$$\begin{aligned} p(\theta) &= p\left(\alpha, h_1^T, h_2^T, \ldots, h_r^T\right) = p(\alpha)\left[\prod p\left(h_t^T\right)\right] \\ &= \left[\prod p(\alpha_i)\, p\left(\sigma_{\eta i}^2\right)\right]\left[\prod p\left(\varphi_{ij}\right)\right]\left[\prod\prod p\left(h_{it}\right)\right]. \end{aligned} \tag{7}$$

Secondly, according to Bayesian, the posterior density of θ is fixed.

$$\begin{aligned} p(\theta \mid y) &\propto p(\theta)\, p(y \mid \theta) \\ &\propto p(\alpha)\left[\prod p\left(h_t^T\right)\right]\left[\prod p\left(y_t \mid \theta\right)\right]. \end{aligned} \tag{8}$$

Thirdly, Bayesian parameters estimation is obtained with Monte Carlo method.

$$\begin{aligned} \widehat{\varphi}_{it} &= \frac{1}{L-s}\sum \varphi_{ii}, \quad i = 1, 2, \ldots, m;\ t = 1, 2, \ldots, T, \\ \widehat{\varphi}_{it} &= \frac{1}{L-s}\sum \varphi_{ij}, \\ &\qquad i \neq j;\ i, j = 1, 2, \ldots, m,\ t = 1, 2, \ldots, T, \\ \widehat{\alpha} &= \frac{1}{L-s}\sum \alpha_i^l, \quad i = 1, 2, \ldots, m;\ t = 1, 2, \ldots, T, \\ \widehat{\sigma}_{\eta i}^2 &= \frac{1}{L-s}\sum \left(\sigma_{\eta i}^2\right)^l, \quad i = 1, 2, \ldots, m,\ l \in (s, L). \end{aligned} \tag{9}$$

The goodness-of-fit of model is a deviance information criterion (DIC) [31] that is based on the posterior distribution of the deviance statistic.

$$D(\theta) = -2\ln p(y \mid \theta) + 2\ln f(y). \tag{10}$$

Here $p(y \mid \theta)$ is the likelihood function for the observed data vector y given the parameter vector θ, and $f(y)$ is some standardizing function of the data alone. The DIC is defined as

$$\begin{aligned} \mathrm{DIC} &= \overline{D} + P_D = 2\overline{D} - D\left(\overline{\theta}\right), \\ \overline{D} &= E\theta \mid y\,[D]. \end{aligned} \tag{11}$$

The fit of a model is summarized by the posterior expectation of the deviance, while the complexity of a model is captured by the effective number of parameters P_D. Smaller values of DIC indicate a better-fitting model.

2.3. Judgment of Volatility Spillover. Firstly, y_{it} is the return of the market i. In order to judge the volatility spillover of different markets, significance test is done for parameter φ_{ij} ($i \neq j$). Null hypothesis is as follows: $H_0 : \varphi_{ij} = 0$ ($i \neq j$).

Standard deviation of parameter $\widehat{\varphi}_{ij}$ is $S_{\widehat{\varphi}_{ij}}$.

$$S_{\widehat{\varphi}_{ij}} = \sqrt{\operatorname{var}\left(\varphi_{ij}\right)} = \sqrt{\operatorname{var}\left(\frac{1}{L-s}\sum \varphi_{ij}\right)}. \tag{12}$$

Here φ_{ij} ($i \neq j$) follows normal distribution. Due to definition of χ^2 distribution, $S_{\widehat{\varphi}_{ij}}$ follows the L degrees of freedom of a χ^2 distribution. So, the statistic is structured.

$$t = \frac{\widehat{\varphi}_{ij}}{S_{\widehat{\varphi}_{ij}}}. \tag{13}$$

If $|t| < t(L)$, the null hypothesis is accepted, which shows that $\varphi_{ij} = 0$ is significant, or the null hypothesis is rejected. Secondly, if parameter $\varphi_{ij} = 0$ $(i \neq j)$ is significant, the volatility spillover effect of the market j to the market i is existing, or there is no effect.

2.4. Settings of Prior Density. It is important to decide joint prior density $p(\theta)$ of unknown parameters and nonobservable variables, before estimating parameters in SV model with MCMC method, and here the key point is to set the initial value.

Due to persistence of volatility, Kim et al. [32] found the matrix, composed of h_{it} and y_{it}, which is a singular matrix, and values of φ_{it} and $\sigma^2_{\eta i}$ are close to zero. If prior value of φ_{it} is close to 1, α goes away, and it becomes the nonidentifier. According to the research of Meng et al. [33], the setting of prior density values is as follows:

$$\begin{aligned}
&\sigma^2_{\eta i} \sim \mathrm{IG}\,(2.5, 0.025)\,, \quad i = 1, 2, \ldots, m,\\
&\varphi^*_{it} \sim \mathrm{beta}\,(20, 1.5)\,,\\
&\varphi^*_{it} = \frac{(\varphi_{it} + 1)}{2},\\
&\qquad\qquad i = 1, 2, \ldots, m,\\
&\alpha_i \sim N\,(0, 0.01)\,,\\
&\varphi_{it} \sim N\,(0, 0.1)\,,\\
&h_{i0} \sim N\left(\alpha_i, \sigma^2_{\eta i}\right),\\
&\qquad\qquad i = 1, 2, \ldots, m,\\
&h_{it} \sim N\left[\alpha_i + \sum \varphi_{ij}\left(h_{i,t-1} - \alpha_i\right), \sigma^2_{\eta i}\right],\\
&\qquad\qquad i = 1, 2, \ldots, m.
\end{aligned} \tag{14}$$

3. Data and Preliminary Analysis

3.1. Data Selection. FFAs contracts are standardized contract to be settled in future, and some of its information is fixed, including routes, quantity of goods, and ship type. Baltic Exchange FFAs routes cover four standard ships, including BFA Capesize (C3, C4, C5, C7, and BCI T/C average), BFA Panamax (P1a, P2a, P3a, and BPI T/C average), BFA Supramax (BSI T/C average), and BFA Handysize (BHSI T/C average). Details are in Table 1.

From history data of trading, percent of Panamax FFAs trading is 54% in 2008, and Capesize is 35%. But in 2009, the Panamax is 42%, and Capesize is 46%. In 2012, they are about 50% and 39%. There may be two reasons. The first is people finding that it is more important for the operators of Capesize to manage risks with FFAs from the global crisis; the second is the larger trading tonnage of Capesize and statistic data by "lot" for Baltic Exchange (one lot equals 1000 mt); therefore, the percent is higher. In addition, China is the biggest iron importer, and the volume of imports is over 70% of the world, which is transported by Capesize ships. So the paper focuses on Capesize FFAs, investigating its volatility spillover. The data set comprises daily observations of Capesize FFAs price, voyage routes C3, C4, C5, and C7, time-charter routes BCIT/C average and BPI T/C average, and spot rate of Capesize. It covers the periods 3 January 2006 to 24 December 2015. The data from the Baltic Exchange are shown in graphical form in Figures 1 and 2. All prices are transformed to natural logarithm difference, according to literatures [1, 34]. In order to investigate the volatility characters of FFAs markets before and after the global financial crisis, the paper chooses a demarcation point of financial crisis, the 15 of September 2008, the day Lehman Brothers went bust, which marks the global financial crisis [35]. There are 664 samples before the financial crisis, and the others are 1819 samples.

Table 1: The information of dry FFAs.

Route	Segment	Route definition	Size (104 DWT)
C3	Capesize	Tubarao/Beilun + Baoshan	15
C4	Capesize	Richards Bay/Rotterdam	15
C5	Capesize	W Australia/Beilun/Baoshan	15
C7	Capesize	Bolivar/Rotterdam	15
BCIT/C average	Capesize	Time-charter average	17.2
P1a	Panamax	Transatlantic	7.4
P2a	Panamax	Cont. trip far east	7.4
P3a	Panamax	Transpacific round voyage	7.4
BPI T/C average	Panamax	Time-charter average	7.4
BSI T/C average	Supramax	Time-charter average	5.2
BHSI T/C average	Handy	Time-charter average	2.8

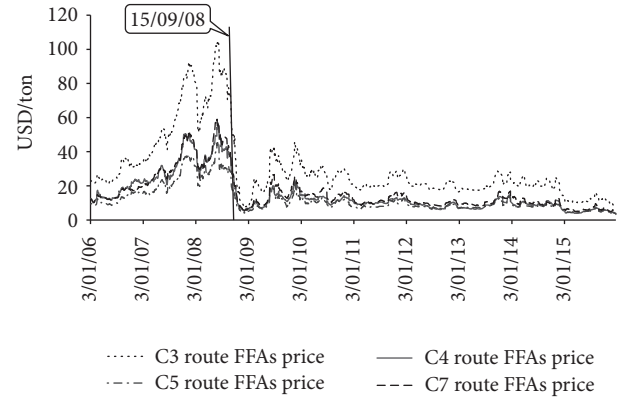

Figure 1: FFAs price of C3, C4, C5, and C7.

3.2. Statistic Characters and Test. The analysis of statistic characters is the basis of studying FFAs price volatilities, and the results are shown in Table 2. According to the results, there are three findings. The first one is high volatility in FFAs markets after financial crisis. The standard deviation is a measure that summarizes the amount by which every value within

Table 2: The statistic characters of returns.

	C3	C4	C5	C7	BCIT/C average	BPIT/C average	BCI T/C
Before 2008 financial crisis							
Mean	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Median	0.002	0	0.001	0.001	0.001	0	0.003
Max	0.078	0.188	0.179	0.199	0.247	0.201	0.146
Min	−0.106	−0.205	−0.244	−0.212	−0.169	−0.122	−0.168
SD	0.018	0.026	0.027	0.022	0.027	0.02	0.029
Skewness	−1.229	−0.207	−1.075	−0.226	1.164	1.596	−0.558
kurtosis	10.504	15.143	18.439	27.996	23.204	26.792	7.939
J-B	1727.638	4090.186	6732.894	17318.23	11461.21	15966.5	710.299
After 2008 financial crisis							
Mean	−0.001	−0.001	−0.001	−0.001	−0.002	−0.001	−0.002
Median	−0.001	−0.001	0	−0.001	−0.003	−0.001	−0.006
Max	0.36	0.251	0.343	0.294	0.678	0.725	0.352
Min	−0.452	−0.304	−0.308	−0.277	−0.975	−0.594	−0.342
SD	0.03	0.029	0.031	0.031	0.081	0.055	0.063
Skewness	−1.471	−0.749	−0.558	−0.436	0.413	0.204	0.639
kurtosis	57.683	27.893	31.426	29.762	31.941	47.374	7.382
J-B	227287.1	47135.22	61335.43	54340.21	63531.48	149248.2	1579.396

Note: SD is standard deviation; J-B is Jarque-Bera statistic.

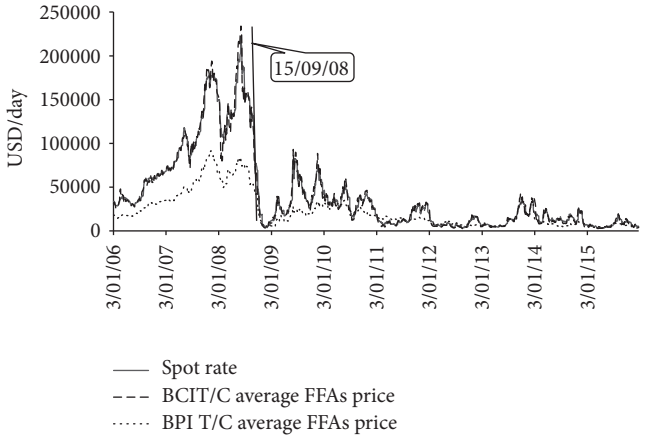

Figure 2: FFAs price of T/C and spot rate.

a dataset varies from the mean. It is used as an indicator of market volatility and therefore of risk. The bigger value of standard deviation, the greater the risk. After crisis, the values of standard deviations increase for all series studied, which indicates high volatility in FFAs markets.

The second finding is negative skew for most series. Skewness is a measure of symmetry or, more precisely, the lack of symmetry. The values of skewness of four voyage routes Capesize FFAs series are negative skew, which indicates that the tail on the left side of the probability density function is longer or fatter than the right side. The values of skewness of BCIT/C average and BPIT/C average FFAs are positive skew, indicating that the tail on the right side is longer or fatter than the left side. For series of spot rates, the skewness value is negative before the crisis but positive after the crisis.

The last one is that all series are leptokurtic. Kurtosis is a measure of the "tailedness" of the probability distribution of a real-valued random variable. The kurtosis of any univariate normal distribution is 3. It is common to compare the kurtosis of a distribution to this value. Distributions with kurtosis greater than 3 are said to be leptokurtic, and distributions with kurtosis less than 3 are said to be platykurtic. From the results, all series are leptokurtic. Higher kurtosis means more of the variance is the result of infrequent extreme deviations, as opposed to frequent modestly sized deviations.

Unit root test is a method testing stationary of time series, and the stationary is the basis of modeling VS-MSV. Augmented Dickey-Fuller Test is applied to stationary test in the research. The null hypothesis is that a unit root exists, and alternative hypothesis is without a unit root. The results of unit root test are in Table 3. According to the test results, all series reject the null hypothesis at 1% level of significant, and it means the series are all stationary, which matches the condition of modeling.

4. Empirical Analysis

4.1. Volatility Spillover among Capesize Voyage Routes FFAs. In the paper, Winbugs software is used, with MCMC method, to estimate the parameters of VS-MSV model, and it studies the volatilities spillover effects among Capesize voyage routes FFAs daily return rate, and the number of iterations is 10000. The results are got when DIC is smallest, shown in Table 4.

According to t-statistic, $t(\infty) < t(1819) < t(1000) < t(664) < t(500)$. At a confidence level of 95%, $t(1000) = 1.646$, $t(500) = 1.648$, and $t(\infty) = 1.6449$. The absolute value of t-statistic for the parameter is not less than 1.648, which means the parameter is significant at 95% confidence level

Table 3: Examination results of ADF test.

	C3	C4	C5	C7	BCIT/C average	BPI T/C average	BCI T/C
ADF test before the crisis	−12.845	−10.598	−15.217	−10.185	−19.752	−20.513	−13.568
1% level	−2.568	−2.568	−2.568	−2.568	−2.568	−2.568	−2.568
ADF test after the crisis	−23.274	−23.119	−23.711	−15.734	−37.776	−37.268	−14.528
1% level	−2.566	−2.566	−2.566	−2.566	−2.566	−2.566	−2.566

Note: all concomitant probabilities are equal to zero.

Table 4: Volatility spillover among Capesize FFAs.

	Before the global financial crisis						After the global financial crisis					
	Value	MC error	2.5%	Median	97.5%	t	Value	MC error	2.5%	Median	97.5%	t
φ_{12}	0.692	0.025	0.302	0.729	0.978	3.162	−0.011	0.007	−0.113	0.000	0.103	−0.185
φ_{13}	0.152	0.010	0.018	0.175	0.299	1.755	0.268	0.016	0.141	0.193	0.577	1.960
φ_{14}	−0.090	0.006	−0.204	−0.080	0.000	−1.754	−0.143	0.012	−0.457	−0.107	−0.060	−1.413
φ_{21}	−0.037	0.011	−0.256	−0.028	0.112	−0.391	0.573	0.012	0.444	0.540	0.814	5.362
φ_{23}	0.089	0.008	−0.047	0.095	0.242	1.205	0.747	0.008	0.666	0.721	0.899	11.137
φ_{24}	−0.124	0.009	−0.280	−0.107	−0.001	−1.564	−0.373	0.009	−0.627	−0.341	−0.318	−4.617
φ_{31}	0.221	0.029	−0.068	0.119	0.788	0.883	0.463	0.013	0.346	0.427	0.775	4.159
φ_{32}	0.657	0.028	0.327	0.785	0.962	2.701	0.128	0.015	−0.210	0.178	0.256	0.945
φ_{34}	−0.093	0.011	−0.294	−0.067	0.029	−0.949	−0.080	0.015	−0.464	−0.021	0.012	−0.598
φ_{41}	0.137	0.062	−0.473	−0.129	0.967	0.253	0.394	0.047	−0.377	0.646	0.704	0.946
φ_{42}	0.916	0.008	0.771	0.936	0.996	13.616	0.946	0.004	0.857	0.950	0.997	26.750
φ_{43}	0.525	0.028	0.187	0.519	0.847	2.137	0.677	0.008	0.596	0.652	0.895	9.205

Note: MC error is Monte Carlo errors.

before the crisis, and after crisis the absolute value of t-statistic should be not less than 1.646.

From Table 4, the three empirical findings are as follows. The first is that the financial crisis can change relationships of spillover effects. Before the crisis, there are no effects from C3 to C4, C5, and C7 and from C5 and C7 to C4, but from C4 and C7 to C3 and C5 and from C3 and C7 after the crisis. The reasons are two. On the one hand, the crisis changes the supply-demand relationships of shipping routes, which could influence the volatility relationships. As we know, the Capesize ship could run on many routes if there are no limits, such as ports draft. After crisis, changes of shipping demands of routes are different, and the transport capacity supplies change accordingly. This would change the volatility relationships between different routes. On the other hand, crisis changes behaviors of participators in FFAs markets and then impact on volatility relationships. After crisis, some investment banks and financing institutions, such as Goldman Sachs and Morgan Stanley, withdrew from FFAs markets.

The second finding is that, before crisis, there are significant spillover effects from C4, C5, and C7 to C3, yet there are no effects from C3 to C4, C5, and C7. The C3 route is the longest in all four voyage routes, about 10 000 nautical miles, and shipping demand is large. The biggest ships always run on this route due to scale economies effect, for example, Valemax ships, with a capacity ranging from 380,000 to 400,000 tons deadweight. Due to limits, such as port draft, it is hard for these large carriers to run on other routes. So there were no significant spillover effects from C3 to other routes. On the contrary, the ships running on C4, C5, and C7 could operate on C3. So volatility of C3 route would be influenced by other routes.

The last one is that there are bilateral effects between C5 and C3. C3 and C5 are both iron shipping routes, and demand of one route would affect the other. Risk of financial crisis transfers between the two FFAs markets, and then there are bilateral spillover effects.

4.2. Volatility Spillover among Capesize FFAs, Panamax FFAs, and Spot Rate. Table 5 is the results of volatility spillover effects between Capesize FFAs and spot rate when the DIC is smallest. From the results, there is a spillover effect from Capesize spot rate to FFAs before the global financial crisis, and there are bilateral spillover effects after crisis. The first reason is that FFAs is derivative of spot rates, and spot market is foundation of FFAs market. Before crisis, the shipping business was brisk, and many firms traded in FFAs markets. And settlements of FFAs depend on spot rates. So there is spillover volatility from spot rates to FFAs. Besides, FFAs market could diversify away risks in spot market and help manage risks and this indicates risks transmission from spot rate to FFAs. The second reason is the mechanism of transmitting of finance risks. After crisis, many companies withdrew from FFAs markets, speculative bubbles burst, and the financial risks transfer to spot rates, which makes spot rate fall.

Table 6 is the results of volatility spillover effects among volatility spillover among Capesize FFAs, Panamax FFAs, and spot rate when the DIC is smallest. From the results, the

Table 5: Volatility spillover between Capesize FFA and spot rate.

	Before the global financial crisis						After the global financial crisis					
	Value	MC error	2.5%	Median	97.5%	t	Value	MC error	2.5%	Median	97.5%	t
φ_{12}	0.851	0.007	0.687	0.847	0.974	11.130	0.245	0.003	0.192	0.245	0.308	9.911
φ_{21}	0.013	0.004	−0.051	0.024	0.070	0.338	0.585	0.008	0.422	0.606	0.655	8.790

Table 6: Volatility spillover among Capesize FFAs, Panamax FFAs, and BCI.

	Before the global financial crisis						After the global financial crisis					
	Value	MC error	2.5%	Median	97.5%	t	Value	MC error	2.5%	Median	97.5%	t
φ_{12}	0.921	0.005	0.811	0.927	0.991	19.015	−0.159	0.005	−0.221	−0.171	−0.047	−3.650
φ_{13}	0.889	0.009	0.688	0.916	0.992	10.461	0.287	0.011	0.114	0.281	0.559	2.807
φ_{21}	0.106	0.004	−0.009	0.113	0.159	2.698	0.888	0.009	0.645	0.911	0.990	10.062
φ_{23}	0.724	0.015	0.459	0.751	0.923	5.368	0.754	0.011	0.479	0.758	0.956	7.378
φ_{31}	−0.0180	0.005	−0.241	−0.192	−0.092	−0.439	0.730	0.021	0.176	0.779	0.971	3.796
φ_{32}	0.0366	0.009	0.147	0.380	0.508	0.433	0.165	0.007	0.031	0.186	0.239	2.752

similar conclusions are with Table 5. Before the crisis, there is no effect from FFAs to spot rate, and after the crisis, there are bilateral effects between FFAs and spot rate. Further, the effects between Panamax and Capesize FFAs are mutually, which is due to the substitutability between Capesize and Panamax in practice.

Above all, there are some suggestions for firms trading in FFAs markets. Firstly, it is important to focus on spillover effects between different voyage routes. Price volatility of one route FFAs is influenced not only by its own early stage but also by volatility coming from other routes, due to spillover effects, which would strengthen the volatility. So firms should consider this before sign a FFAs contract. Taking C3 route as an example, if one company would buy a FFAs contract settlement one month later, some factors should be considered for analyzing price volatility, such as history volatility of C3 route and spillovers from C5. Secondly, according to spillover from spot rate to FFAs, the changes of spot markets would affect FFAs markets. So it is necessary to pay attention to factors influencing spot rates, such as supply and demand. Thirdly, there are bilateral relationships between Panamax time-charter FFAs and Capesize time-charter FFAs, so it is important to focus on some factors affecting Panamax shipping market when trading in Capesize FFAs markets.

5. Conclusion

The paper studies the volatility spillover effects in Capesize forward freight agreement market using VS-MSV model, and the results show that the effects are different in different routes and markets. The effects exist between certain Capesize routes, and the effects are from spot to FFAs before the global financial crisis, yet bilateral after the crisis.

Some conclusions are as follows. (1) Spillover effects of Capesize FFAs markets are influenced by financial crisis, which changes supply-demand relationships in shipping market and behaviors of participators in FFAs markets. (2) There are significant spillover effects from C4, C5, and C7 to C3, yet there are no effects from C3 to C4, C5, and C7; there is effect from C5 to C3 and from C3 to C4 and C5 after crisis. (3) There is a spillover effect from Capesize spot rate to FFA before the global financial crisis, and there are bilateral spillover effects after crisis. (4) Bilateral effects exist between FFAs and spot rate.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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Research Article

An Integrated Method of Supply Chains Vulnerability Assessment

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Supply chain vulnerability identification and evaluation are extremely important to mitigate the supply chain risk. We present an integrated method to assess the supply chain vulnerability. The potential failure mode of the supply chain vulnerability is analyzed through the SCOR model. Combining the fuzzy theory and the gray theory, the correlation degree of each vulnerability indicator can be calculated and the target improvements can be carried out. In order to verify the effectiveness of the proposed method, we use Kendall's tau coefficient to measure the effect of different methods. The result shows that the presented method has the highest consistency in the assessment compared with the other two methods.

1. Introduction

With the rapid development of economy and technology, the competition among enterprises has become competition between supply chain. Because of the frequency and intensity of terrorist attacks, SARS, hurricane, and series of other disasters and crises [1–3], supply chain management has aroused widespread concern. In 2011, Thailand suffered the worst flooding in the past fifty years which led to a fatal damage for some giant industrial park around Bangkok, and the flooding resulted in the supply chain disruption of motor industries, electronic components, and hard disk [4]. As the supply chain structure becomes more and more complicated, the supply chain capacity that respond to the disruption is weaker than before [5, 6], and thus the supply chain vulnerability is more serious [7]. Researches on the vulnerability originated in the 1970s when White (1974) first proposed the "vulnerable" concept and it is a new emerging research field in supply chain management. Christopher and Peck [8] defined supply chain vulnerability as "a kind of exposure to serious disturbance." In the researches of natural disasters and crisis management, Blaikie et al. [9] defined vulnerability as the ability of an individual or organization to predict, process, resist, and recover. In the researches of ship supply chain, Barnes and Oloruntoba [10] described the vulnerability as "a vulnerable constitution that leads to loss which caused by existing organizations or functional activity or external condition." Based on various definitions, we consider that the vulnerability is an instability and destructiveness that caused by supply chain external and internal risks. Supply chain vulnerability is an inherent trait of the supply chain, which is determined by the structure and characteristics of the supply chain itself.

Currently, researches on supply chain vulnerability mainly concentrated on its definition, connotation, influence factors, and other aspects, while little concern is paid to supply chain vulnerability assessment [11]. Based on interference, performance losses, the relationship between them, and other factors, Albino and Garavelli analyzed the sensitivity of supply chain systems under the condition that time is known and interference occurs randomly; then the supply chain vulnerability was evaluated [12]. Prater et al. [13] used five cases in the paper to achieve optimal coordination between agility and complexity through controlling supply chain risk factors and changing supply chain complexity. Zhong and Xie [14] proposed "3P" management principles and supply chain

vulnerability management principles to prevent and respond to damage at the tactical level. In the view of specialization of supply chain, Barnes and Oloruntoba [10] analyzed the characteristics of the entire supply chain using the special case, and they concluded that it is the complexity of the interaction between marine operations and supply chain that caused the vulnerability. In 2000, Svensson, representative scholar in the supply chain vulnerability, built a supply chain vulnerability theoretical framework and made a qualitative description and assessment of the vulnerability through the disturbance source, category, and logistics mode [15]. After two years, he calculated the vulnerability again based on time and relationship [16]. In order to enrich the study, he assessed the supply chain vulnerability from time, function, and relationship's three dimensions in 2004 [17]. Peck introduced the network theory and complex systems into the interactive production system supply chain conceptual model and analyzed the four levels from multiangles [18]. D. Bogataj and M. Bogataj [19] evaluated the vulnerability from the perspective of vulnerable point and analyzed the input-output tables and the relationship between storage and delivery, using the dynamic NPV method which can find the relationship of before and after items; then he concluded the weak link of the supply chain and predicted the vulnerability point. Based on the vulnerability index, Stephan and Wagner [20] proposed a method to confirm the validity of the policy by comparing different industry or enterprise vulnerability index. With the development of extensive, Fang et al. [21] proposed vulnerability assessment and early warning model for small and medium-sized enterprises intellectual property.

To sum up, the existing researches have established theoretical framework to evaluate the supply chain vulnerability. However, these basically are limited to the qualitative framework. Therefore, we utilize the FMEA (failure mode and effect analysis) method, which is a way for prospective reliability analysis and safety assessment. It analyzes every failure mode that existed in the system, and it calculated risk priority number (RPN) for the consequences of all failure modes [22]. According to the value of RPN, we make a quantitative assessment of the failure modes and take corresponding measures to prevent and avoid the potential failure mode if necessary. However, the traditional FMEA method does not recognize the importance of the relationship between all the failure modes and every decisive factor in the vulnerability, and the traditional FMEA method makes its evaluation effect limited when the experts' evaluation language is qualitative and subjective. Considering the above conditions, we present an integrated method using the fuzzy theory and the gray relational theory to solve the above problems. The present method can help business managers implement the improvements of supply chain vulnerability.

2. Methodology and Assessment Process

2.1. Methodology. FMEA, namely, failure mode and effect analysis, in fact, originated in the 1950s. Because of the significant value in safety and reliability assessment, FMEA has developed rapidly and has been widely used in many areas such as the nuclear industry, automotive, machinery, aerospace, electronics, and ships. It use three aspects for assessment. They are severity (S), occurrence (O), and detection (D) [23]. It is a powerful tool for defining, identifying, and eliminating potential failures from the system, design, process, or service before they reach the customer [24]. Severity is the degree of the effect of the potential failure mode on customers; occurrence refers to the possibility of the occurrence of the specific failure mode; detection describes the possibility that the current system cannot recognize the failure modes or reasons. The traditional FMEA method has two following disadvantages in practical application.

First, the traditional FMEA method to assess products or system risks merely depends on RPN which can lead to large problems in the actual situation. In the traditional FMEA, we get RPN simply through the product of the three factors: severity (S), occurrence (O), and detection (D). In traditional FMEA, the relative importance of each factor is not considered and the three factors are given the same weight. Meanwhile, the different factors may be multiplied to get the same RPN, but corresponding degree of risk is inconsistent, which makes the RPN inefficient in practical application in various failure modes of the level of risk assessment.

Second, the application effect of FMEA was limited because of the limited experience and knowledge that the experts have. To apply FMEA method, you should set up a committee of experts first, and experts grade every factor by their experience and knowledge. In this process, experts need to have a profound understanding, investigation, and research, but it is difficult to describe their experience and knowledge because the subjective of the language, so the traditional FMEA can not make accurate judgments; thus there is a limit to the effect of traditional FMEA.

From the preceding analysis, we can find that there are a lot of factors that influenced the supply chain vulnerability in the assessment index system, and many factors mutually affect each other, so we need a comprehensive approach to integrating the FMEA method to assess the vulnerability. Meanwhile, the comment that the FMEA expert team members assess often expressed ambiguous. In order to modify the defects of the traditional FMEA method and consider the characteristics of supply chain vulnerability influence factors, FMEA method is combined with fuzzy theory and gray Correlative Method to evaluate and rank the RPN.

2.2. Assessment Process. When using the FMEA method, we should first give the operational model a clear definition, then analyze the potential failure modes that existed in every process, and confirm the cause of potential failure modes. Next, we use the models to assess all failure modes, rank the vulnerability, take preventive measures according to the vulnerability value, and estimate the effect of the measures. In this paper, we give a special study on supply chain vulnerability which is based on traditional FMEA operation steps, so the supply chain based on FMEA vulnerability assessment process is shown as Figure 1.

3. Supply Chain Vulnerability Analysis

3.1. Supply Chain Vulnerability Analysis. We adopted the supply chain operations reference model (SCOR) that is

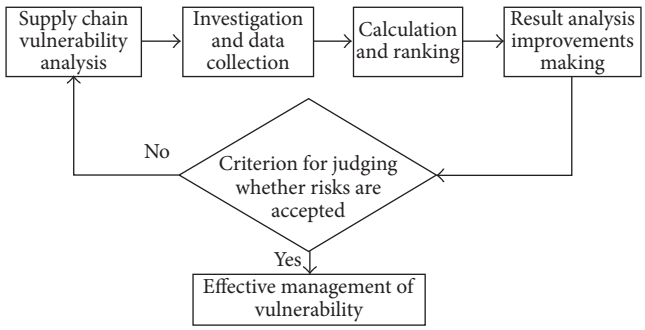

Figure 1: Assessment process.

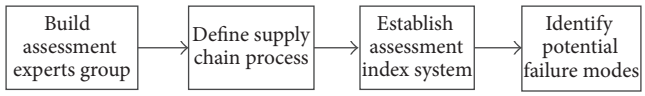

Figure 2: SC vulnerability analysis process.

developed and authorized by the Supply Chain Council, so that we can better identify failure modes existing in the supply chain process and assess the supply chain vulnerability. Based on the SCOR model, the supply chain vulnerability analysis process is given in Figure 2.

Ten experts from academia and industry fully aware of the supply chain operation in the manufacture industry are divided into two groups. Group 1 adapt the SCOR model to conceptualize the supply chain vulnerability analysis, and group 2 validate the results of group 1. They define the supply chain operation management processes as follows: Plan, Source, Make, Deliver, and Return, denoted as P, S, M, D, and R. And they establish competitive performance goals. The second configuration layer is composed of 26 kinds of core processes through a full discussion. In the third decomposition layer, the second layer is detailed and specific, which makes the process more specific and gives the company's competence ability in selected markets. At the third layer, the experts group analyze the process, identify failure modes, and conclude consequences.

3.2. Supply Chain Vulnerability Assessment Index System and FMEA Analysis. In reviewing the relevant research results, the experts group built a supply chain vulnerability assessment index system. We define the second layer as P_i, S_i, M_i, D_i, R_i, and its corresponding potential failure modes as P_iF_j, S_iF_j, M_iF_j, D_iF_j, R_iF_j, where $i = 1, 2, \ldots,\ j = 1, 2, \ldots$.

(1) Planning Process Failure Analysis. In the SCOR model, "Plan" is the processes that balance aggregate demand and supply to develop a course of action which best meets sourcing, production, and delivery requirements. The planning processes include confirming, ranking, and consolidating needs; confirming, evaluating, and integrating resources and capabilities; balancing resources, capabilities, and needs; and making plans.

(2) Sourcing Process Failure Analysis. "Source" is the processes that procure goods and services to meet planned or actual demand. Sourcing processes include confirming supply source; selecting vendors and negotiating procurement of raw materials; product distribution arrangement; accepting products; checking products; transferring products; authorizing payments; and other steps.

(3) Making Process Failure Analysis. "Make" is the processes that transform product to a finished state to meet planned or actual demand. The making processes include arranging production activities; distribution of raw materials and products; production and testing; packaging; storage.

(4) Delivering Process Failure Analysis. "Deliver" is the processes that provide finished goods and services to meet planned or actual demand, typically including order management, transportation management, and distribution management. The delivering processes include processing queries, offering, and receiving; registration and verification of orders; reserving inventory and determining distribution date; combining orders; distribution packaging; loading and generating and distributing records; transporting products; customer reception and checking products.

(5) Returning Process Failure Analysis. "Return" is the processes associated with returning or receiving returned products for any reason. These processes extend into postdelivery customer support. The return processes include acknowledging of customer returning products; disposal of returned products; requesting a return privilege; arranging distribution; recycling returned products; and other processes.

4. Model

The proposed integrated FMEA model can be described as the following steps in detail based on the basic FMEA model.

4.1. Establishment of Assessment Index System. According to the previous introduction to supply chain vulnerability identification, we could put forward the factors set as follows: $U = \{P, S, M, D, R\}$ and further divide them, and the next layer factor is set as $P = \{P_1, P_2, P_3\}$, $S = \{S_1, S_2\}$, $M = \{M_1, M_2, M_3\}$, $D = \{D_1, D_2, D_3\}$, $R = \{R_1, R_2, R_3, R_4\}$. If there is a next layer, we continue to define it.

4.2. Establishment of Assessment Set. We establish the assessment set by selecting, "very high," "high," "higher," "medium," "lower," "low," and "very low," seven semantic items [25].

$$V = \{\text{very high (VH)},\ \text{high (H)},\ \text{little high (VH)},\ \text{medium (M)},\ \text{little low (LL)},\ \text{low (L)},\ \text{very low (VL)}\}. \quad (1)$$

The corresponding meaning of all semantic items is shown in Table 6. By using the seven semantic items, experts assess the potential failure modes in the supply chain and give fuzzy scores to the severity S, occurrence O, and detection D. According to the seven semantic items, we obtain the corresponding clear number by using fuzzy mathematical

theory and method and establish the assessment set as shown in Table 6.

We used experts scoring method to determine the weight of each failure mode. Assuming that there are n experts and i failure modes, the weight of failure mode i given by expert k is recorded as υ. The corresponding fuzzy semantic value of triangular fuzzy number is through the use of the Delphi method; experts make decisions depending on their own experience and knowledge. The ability of expert k is defined as ∂_k and the fuzzy assessment of a certain critical factor in the failure mode is defined as x_k, which can be expressed by the triangular fuzzy number as $x_k = (a_k, b_k, c_k)$. According to the experts' experience, we can get the value of the key factor fuzzy triangles corresponding to the digital fuzzy semantic items by the following equation (note that $\sum_{k=1}^{n} \partial_k = 1$, $\partial_k \in (0, 1)$):

$$\begin{aligned} a &= \sum_{k=1}^{n} \partial_k a_k \\ b &= \sum_{k=1}^{n} \partial_k b_k, \\ c &= \sum_{k=1}^{n} \partial_k c_k. \end{aligned} \tag{2}$$

We use fuzzy theory to calculate the formula, which is proposed by Xiao and Li [26]. Formula is shown as follows:

$$\begin{aligned} C(x) = \frac{1}{2(1+N)} * a + \frac{N + 2NM + M}{2(1+N)} * b \\ + \frac{1}{2(1+M)} * c. \end{aligned} \tag{3}$$

For the basic factor set having three layers, we added variable h. Then, the weight of the failure mode i was calculated by

$$\begin{aligned} \pi_i = \frac{1}{n} \sum_{k=1}^{n} {\pi_{ki}}^h \\ (k = 1, 2, \ldots, n;\ i = 1, 2, \ldots, m;\ h = 1, 2, 3). \end{aligned} \tag{4}$$

4.3. Establishment of FMEA Table. In the previous section, we applied fuzzy number and fuzzy theory and obtained the corresponding number of fuzzy semantic items assessed by an expert team. Next, FMEA assessment team will assess the various failure modes by using the fuzzy semantic items. In this process, we need to establish an expert survey and statistics table in order to obtain the data.

After experts scored the failure mode, we can get every layer factor's weight which ups to the average scores. In the traditional FMEA, experts score in the condition that every layer factors unrelated. In fact, the factors of every layer exist hierarchical relationships. By using probability tree theory, we calculate the value of weight considering hierarchical relationships of factors. If we used θ to represent the RPN coefficient of every failure mode, then $\theta = {\pi_i}^h {\pi_i}^{h-1} {\pi_i}^{h-2}$ (${\pi_i}^h$ indicates the weight of the failure mode regardless of the hierarchical relationships, ${\pi_i}^{h-1}$ indicates the weight of the failure mode corresponding to the upper layer, and ${\pi_i}^{h-2}$ indicates weight of the failure mode corresponding to the next higher layer of the upper layer).

4.4. Determination of Vulnerability Level. According to the formula of improved risk priority number RPN $= \theta * S * O * D$, we can get RPN which indicates the level of risk of various failure modes. But the crux of the matter is that RPN can help managers make decisions. Then, the degree of gray correlation between the evaluation vectors of each scheme is calculated by the gray relational grade, and the decision and evaluation vector in the best scheme are obtained.

Step 1 (establishing comparison matrix). We assume that there are p types of failure modes. Each failure mode is expressed by i, and x_i illustrates failure mode i. When computing, there are S, O, D, three variables of each failure mode, so the data shows failure mode i represented as $x_i = \{x_i(t),\ t = 1, 2, 3\}$, whose values can be got by (3). On the basis of the method mentioned above, to reflect various of failure mode, we establish the comparison matrix as follows:

$$\begin{aligned} X_i(t) = \{x_i(t)\} &= \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{pmatrix} \\ &= \begin{pmatrix} x_1(1) & x_1(2) & x_1(3) \\ x_2(1) & x_2(2) & x_2(3) \\ \vdots & \vdots & \vdots \\ x_p(1) & x_p(2) & x_p(3) \end{pmatrix}. \end{aligned} \tag{5}$$

Step 2 (establishing reference matrix). Failure mode risk ranking should be based on certain reference standards. In general, we choose the best or worst value as a reference. The worst value of each variable is chosen to build a reference matrix as follows:

$$\{x_0(t)\} = \begin{pmatrix} \mathrm{VH} & \mathrm{VH} & \mathrm{VH} \\ \mathrm{VH} & \mathrm{VH} & \mathrm{VH} \\ \vdots & \vdots & \vdots \\ \mathrm{VH} & \mathrm{VH} & \mathrm{VH} \end{pmatrix}. \tag{6}$$

Step 3 (calculating gray correlation coefficients). When it comes to the gray correlation theory, the following formula can be obtained:

$$\begin{aligned} &\lambda(x_0(t), X_i(t)) \\ &= \frac{\min_i \min_t \left|x_0(t) - x_i(t)\right| + \upsilon \max_i \max_t \left|x_0(t) - x_i(t)\right|}{\left|x_0(t) - x_i(t)\right| + \upsilon \max_i \max_t \left|x_0(t) - x_i(t)\right|}, \end{aligned} \tag{7}$$

where υ is distinguishing coefficient, with the value in interval (0,1), normally $\upsilon = 0.5$.

Table 1: Planning process assessment index and failure mode analysis.

First-layer factors	Second-layer factors	Potential failure modes
Plan P	Strategy P_1	P_1F_1: unclear strategic positioning
		P_1F_2: high positioning
		P_1F_3: low positioning
		P_1F_4: inaccurate plan data
		P_1F_5: supply chain strategy adjustment
		P_1F_6: inconsistent strategic objectives among supply chain members
		P_1F_7: failed strategic investment
	Culture P_2	P_2F_1: insufficient understanding and emphasis of supply chain managers on the multicultural conflict risk
		P_2F_2: low quality of the staff cultural skills
		P_2F_3: weak risk awareness and corporate risk culture
		P_2F_4: inconsistent corporate cultural values
	Demand P_3	P_3F_1: customer loss
		P_3F_2: low satisfaction of customers' needs
		P_3F_3: demand fluctuations
		P_3F_4: poor sales reputation
		P_3F_5: many competitive alternatives

Step 4 (calculating gray correlations). Because of the different influence on risk, the variable of failure mode has different weights. Assuming the weight of variables is ξ_t, so the correlation degree is computed by the following equation [27]:

$$\mu(x_0, x_i) = \sum_{t=1}^{3} \xi_t \left\{\lambda\left(x_0(t), X_i(t)\right)\right\}. \quad (8)$$

Note that $\sum_{t=1}^{3} \xi_t = 1, \xi_t$ is computed from the front expert questionnaire statistics.

Step 5 (ranking). Finally, according to formula $\theta * \mu(x_0, x_i)$, we could calculate the correlation degree in the case of considering single weight of failure mode and three critical factors of weight of each failure mode. Then, we sort the correlation degree in descending order. Determine the RPN and make target improvements.

5. Case Study

5.1. Case Introduction. Shipbuilding Yard RS was founded in 2005, which is mainly engaged in shipbuilding, marine engineering, marine engine manufacturing, and construction machinery, and it concentrates on the relevant customers and markets of oil and gas industry. According to the 2010 annual report, it had the largest proportion of business in Brazil, China, Germany, and Turkey, and it is the fastest growing private shipbuilding company in China. According to the British maritime agency Clarkson report, RS is also the largest shipbuilding enterprises at present in China by calculating hand-held orders. In October 2012, a RS's subsidiary, named RS Maritime, which aims to achieve the development strategy of its upgrading and transformation and develop the ocean engineering operations which are high value-added and rapidly increasing, was set up in Singapore.

The company attaches great significance to the vulnerability of the supply chain. As a result, the FMEA assessment team is set up to assess the enterprises' vulnerability. Because of the difficulty in obtaining the accurate risk factors, the semantic variables are used in Table 8 to score the potential failure modes. The FMEA assessment team includes 5 cross-department assessment members, and it is mainly used as the scoring expert group which is named Expert Group 1. Owing to the different expertise and background of the experts, the importance and ability of them are also different. On these grounds, different relative weights are given as follows: 0.3, 0.2, 0.2, 0.2, and 0.1. In order to verify the effectiveness of Expert Group 1 construction index and scoring results, we ask the company to set up another expert group, named Expert Group 2, which is mainly used as validation expert group.

5.2. Model Application

5.2.1. Establishment of Assessment Index System. We have a thorough initial assessment with a total of 68 third-layer factors and 15 second-layer factors (Tables 1–5). In this part, Expert Group 1 is provided with questionnaires to identify the most important variables in their opinion, from Tables 1–5. After a discussion of the Expert Group 1, they summarized a set of vulnerability assessment index system for the RS. Then, the index system is presented to an additional independent group (Expert Group 2) for the purpose of model and result validation, so the index system is corrected and improved, and eventually we obtained the most suitable index system for RS (see Appendix in Supplementary Material available online at http://dx.doi.org/10.1155/2016/2819238).

5.2.2. Establishment of Fuzzy Assessment Set. In order to get clear numbers of corresponding fuzzy semantic items, Expert Group 1 scores the fuzzy semantic items. According

Table 2: Sourcing process assessment index and failure mode analysis.

First-layer factors	Second-layer factors	Potential failure modes
Source S	Purchasing S_1	S_1F_1: high purchasing price
		S_1F_2: frequent fluctuations in exchange rates
		S_1F_3: inappropriate supplier selection
		S_1F_4: unable to deliver goods on time
		S_1F_5: low quality of procurement product
		S_1F_6: irresponsible purchase person
		S_1F_7: purchasing accident
		S_1F_8: acceptance lax of procurement materials
	Supply S_2	S_2F_1: key suppliers failing to bankruptcy or loss
		S_2F_2: supplier business outsourcing
		S_2F_3: suppliers' insufficient production capacity
		S_2F_4: unable to deliver goods on time
		S_2F_5: insufficient supplier technical innovation capability
		S_2F_6: shortages of raw materials market
		S_2F_7: inadequate supply elasticity of supplier

Table 3: Making process assessment index and failure mode analysis.

First-layer factors	Second-layer factors	Potential failure modes
Make M	Environment M_1	M_1F_1: macroeconomic fluctuation
		M_1F_2: political instability and government intervention
		M_1F_3: industrial policy constraints
		M_1F_4: natural disasters and so forth.
		M_1F_5: insufficient in public utilities supply
	Production M_2	M_2F_1: improper control of the production process
		M_2F_2: inelastic production capacity
		M_2F_3: low level of information sharing
		M_2F_4: technical level restrictions
		M_2F_5: labor cost Rising
		M_2F_6: talent loss and labor dispute
		M_2F_7: less rigorous of production inventory control
	Control M_3	M_3F_1: imperfect financial system
		M_3F_2: imperfect job security system
		M_3F_3: failed risk response mechanism
		M_3F_4: inappropriate product cost control
		M_3F_5: substandard product
		M_3F_6: intellectual property rights and other legal issues

Table 4: Delivering process assessment index and failure mode analysis.

First-layer factors	Second-layer factors	Potential failure modes
Deliver D	Relation D_1	D_1F_1: self-interested behavior of partners
		D_1F_2: distrust between partners
		D_1F_3: inequitable benefits distribution among partners
		D_1F_4: unfair competition between partners
	Transportation D_2	D_2F_1: inappropriate choice of transportation routes and means
		D_2F_2: immature delivery technology or distribution equipment failure
		D_2F_3: product damage or loss
		D_2F_4: unscientific delivery personnel management
		D_2F_5: inappropriate distribution model
		D_2F_6: errors or delays in delivery
	Origination D_3	D_3F_1: irrational supply chain structure
		D_3F_2: improper delegation of supply chain authority

Table 5: Returning process assessment index and failure analysis.

First-layer factors	Second-layer factors	Potential failure modes
Return R	Return way R_1	R_1F_1: no consensus with customer
		R_1F_2: no consensus with supplier
	Return route R_2	R_2F_1: improper return route
	Return procedure R_3	R_3F_1: imperfect return process and rules
	Return management R_4	R_4F_1: imperfect return asset management
		R_4F_2: imperfect return distribution management
		R_4F_3: improper return inventory management
		R_4F_4: incomplete return collection data

Table 6: Corresponding meaning of semantic items.

Semantic items	Severity	Occurrence	Detection
Very low	Products are not affected	Failure hardly occurs	Almost all detected
Low	Products are slightly affected	Failure rarely occurs	The probability that failure is not detected is low
Little low	Some characteristics are slightly affected but product function properly	Failure occurs less	The probability that failure is not detected is relatively low
Medium	Product can be used, but some important characteristics are affected, while there is no dissatisfied customer	Failure occurs occasionally	Failure is not occasionally detected
Little high	Product can be used, but some important characteristics are affected strongly, some customers are not satisfied	Failure occurs frequently	Failure cannot be detected occurs frequently
High	Product has problems and has lost basic function	Failure occurs repeatedly	Failure most cannot be detected
Very high	Products are complete lost basic function, and threaten personal safety or violate laws	Failure is almost inevitable	Failure is almost undetectable

Table 7: Rating levels for decision-making factor i of failure mode FM_i.

Expert	∂_k	Very low (VL)	Low (L)	Little low (LL)	Medium (M)	Little high (LH)	High (H)	Very high (VH)
1	0.3	(0,1.3,2.8)	(0.8,2.3,3.8)	(2.7,4.5,6.3)	(3.8,5.8,7.8)	(5.3,7.1,8.8)	(7.8,9.1,9.9)	(8.8,10,10)
2	0.2	(0,1.3,2.6)	(0.6,2.1,3.6)	(2.2,4.1,6.6)	(3.3,5.3,7.6)	(4.5,6.5,8.7)	(7.1,8.9,9.9)	(8.3,10,10)
3	0.2	(0,1.3,2.3)	(0.7,2.4,3.7)	(2.4,4.5,6.7)	(3.5,5.5,8.2)	(5.1,7.1,9)	(7.5,9.3,9.9)	(8.5,10,10)
4	0.2	(0,1.3,3)	(0.7,2.3,4)	(2.6,4.5,6.5)	(3.6,5.1,8)	(5.3,6.5,8.9)	(8.1,9.2,9.9)	(9.2,10,10)
5	0.1	(0,1.3,2.7)	(0.6,2.1,3.7)	(2.4,4.5,6.4)	(3.4,5.6,8)	(5,6.8,8.9)	(7.6,8.9,9.9)	(8.6,10,10)
Total	1	(0,1.3,2.7)	(0.7,2.7,3.8)	(2.5,2.4,6.4)	(3.6,5.6,7.9)	(5.1,6.8,8.9)	(7.6,9.1,9.9)	(8.7,10,10)

to the seven items proposed in the previous section, Expert Group 1 assesses fuzzy decision-making factor of each failure mode. The following table shows the expert scores, which are triangular fuzzy numbers. ∂ is the relative weight mentioned above.

Based on (3) and the scores in Table 7, clear numerical values of fuzzy semantics can be calculated. The results of these calculations are summarized in Table 8.

5.2.3. Establishment of FEMA Table and Weight Scoring Table. Owing to space limitations, detailed FMEA tables are not displayed in the body part but in Appendix A. In addition, FEMA scoring is shown in Table A1 and the weights at all layers scoring are shown in Table A2. When establishing FMEA table, we omit corresponding causes and results of failure modes on the basis of the practical needs, but we have improved the traditional FMEA table to be applicable for the macro supply chain system.

Table 8: Corresponding clear number of fuzzy semantic items.

Items	VL	L	LL	M	LH	H	VH
Clear number	1.3	2.3	4.5	5.7	6.9	9	9.8

5.2.4. Processing of Data. By summarizing statistics of expert scoring sheets, we got Tables B1 and B2 in Appendix B. On the basis of the clear number in Table 8, we get decision-making

Table 9: Risk ranking of third-layer factors based on FEMA and gray correlation.

Third-layer factors	Weight	Correlation	Ranking
P_1F_1	0.04	0.0260	11
P_1F_2	0.03	0.0198	14
P_2F_1	0.02	0.0128	20
P_2F_2	0.02	0.0116	22
P_3F_1	0.02	0.0163	16
P_3F_2	0.02	0.0136	19
P_4F_1	0.02	0.0119	21
P_4F_2	0.01	0.0062	25
P_4F_3	0.01	0.0069	24
P_4F_5	0.01	0.0064	26
S_1F_1	0.07	0.0433	5
S_1F_2	0.05	0.0315	9
S_2F_1	0.08	0.0501	3
S_2F_2	0.04	0.0255	12
M_1F_1	0.06	0.0432	8
M_1F_2	0.06	0.0385	6
M_1F_3	0.06	0.0482	4
M_2F_1	0.05	0.0373	7
M_2F_2	0.04	0.0267	10
M_2F_3	0.03	0.0197	15
D_1F_1	0.02	0.0145	17
D_1F_2	0.03	0.0208	13
D_2F_1	0.02	0.0137	18
D_2F_2	0.01	0.0055	27
D_2F_3	0.02	0.0106	23
R_1F_1	0.08	0.0506	2
R_1F_2	0.08	0.0630	1
Sum	1.0	—	—

factors set named B2. Owing to space limitations, we do not list the source data but show the average index weight set B3.

5.2.5. Determination the Level of Vulnerability

(1) Establishing Related Matrix. According to decision-making factor set obtained in the previous step, we establish a comparison matrix and choose the worst value including $x_i(t)$ and $x_0(t)$ to establish reference matrix.

(2) Calculating Gray Correlation Coefficient. Taking $\upsilon = 0.5$, we compute the gray correlation coefficient between decision-making factor variables and reference values by (7) and get $\lambda(x_0(t), X_i(t))$.

(3) Calculating Gray Correlation Degree. On the basis of (8) (ξ_t, available in Appendix), we can get the following data: (0.64964,0.65921,0.63872,0.58098,0.81740,0.68236,0.59689, 0.61506,0.69091,0.57574,0.61907,0.63095,0.62653,0.63831, 0.71990,0.64093,0.80330,0.74667,0.66641,0.65730,0.72529, 0.69363,0.68583,0.54514, 0.53203,0.56261,0.73313).

(4) Ranking Vulnerability Level. Again, according to $\theta * \mu(x_0, x_i)$, we obtain the risk ranking summarized in Tables 9, 10, and 11.

Table 10: Risk ranking of second-layer factors based on FEMA and gray correlation.

Second-layer factors	Weight	Correlation	Ranking
P_1	0.068	0.0458	6
P_2	0.04	0.0244	11
P_3	0.044	0.0299	9
P_4	0.048	0.0314	8
S_1	0.1248	0.0748	5
S_2	0.1152	0.0756	4
M_1	0.168	0.0867	2
M_2	0.112	0.0837	3
D_1	0.048	0.0353	7
D_2	0.052	0.0298	10
R_1	0.18	0.1136	1
Sum	1	—	—

Table 11: Risk ranking of first-layer factors based on FEMA and gray correlation.

First-layer factors	Weight	Correlation	Ranking
P	0.2	0.1315	3
S	0.24	0.1504	2
M	0.28	0.2136	1
D	0.1	0.0651	5
R	0.18	0.1136	4
Sum	1	—	—

5.3. Result Analysis. From Table 11, we conclude that five first-grade indicators ranking is make > source > plan > return > deliver. The vulnerability of RS is chiefly reflected in three aspects: make, source, and plan. The make risk is the largest so its weight is the heaviest. Meanwhile, factor of source is the second place in the secondary indicators of manufacturing, which indicates that the manufacturing process attaches great importance to the shipbuilding supply chain and it is the most vulnerable part and the most error-prone part, which have relations with the characters of the shipbuilding enterprises industry. Source is nearly as significant as make. Especially, the overcapacity of RS should be taken seriously. Furthermore, source is also important in the second part of the shipbuilding supply chain. Owing to the expanding scope of business and cost savings resulting from zero inventory, RS has higher and higher requirements for the raw materials. RS becomes increasingly dependent upon suppliers, but suppliers which lead to risk are among all failure modes that are ranking in the top place, which should concern more about the supply chain flexibility when pursuing efficiency and low cost at the same time. Large-scale shipbuilding overseas orders make the process of planning more crucial and higher request for the accurate strategic plan and the effective building. What requires more attention is that the weightof the last link of supply chain in return

Table 12: Comparison of τ value of various methods.

	Improved FMEA	Average	Only fuzzy theory FEMA
τ_1	0.69	0.16	0.45
τ_2	0.71	0.17	0.50
τ_3	0.70	0.36	0.46
τ_4	0.68	0.32	0.45
τ_5	0.65	0.33	0.37
τ_6	0.65	0.11	0.32
τ_7	0.71	−0.01	0.24
τ_8	0.69	0.00	0.43
τ_9	0.73	0.28	0.53
τ_{10}	0.75	0.13	0.64
τ	0.70	0.18	0.44

process is not big. It is calculated ranking top in the layer 3 risk factors, and they are company cancel the order and contract renegotiation, which is the first and second, respectively. The mismanagement between the firm and the demand side management causes that there is a large-scale overseas of invalid orders.

5.4. Comparison with Other Methods. In order to verify the validity of improved FMEA in evaluating the supply chain, Expert Group 2 is also requested to score the FMEA table and weight table. In this paper, we use Kendall's tau coefficient [28, 29] to verify the quality of order-preserving.

Given two rating score vectors $\{a_i\}_{i-1}^n$ and $\{b_i\}_{i-1}^n$, C_{ij} defined as

$$C_{ij} = \begin{cases} 1 & \text{If } \left(a_i < a_j \text{ and } b_i < b_j\right) \text{or } \left(a_i > a_j \text{ and } b_i > b_j\right) \text{or } \left(a_i = a_j \text{ and } b_i = b_j\right) \\ 0.5 & \text{If } \left(a_i = a_j \text{ and } b_i \neq b_j\right) \text{or } \left(a_i \neq a_j \text{ and } b_i = b_j\right) \\ 0 & \text{Other.} \end{cases} \tag{9}$$

Then, the number of concordant pairs is $C = \sum_{i-1}^{n} \sum_{j=i+1}^{n} C_{ij}$. Based on the above definition, Kendall's tau rank-correlation coefficient can be calculated, namely, τ. Besides, τ value has three properties: (1) if the two ratings imply the same ranking, $\tau = 1$. Otherwise, $\tau = -1$. (2) For all the cases, τ value lies between −1 and 1. (3) One property of τ index is as follows: the larger value τ that shows order-preserving is better and the method applied during sorting is more in line with the actual situation. Table 12 shows that the improved FMEA result is more in line with the actual situation compared with the other two methods.

6. Conclusions

In this study, an improved FMEA is provided to assess the supply chain vulnerability. The main results are as follows:

(1) With lots of expert interviews and investigations of related literature, we establish the supply chain vulnerability assessment index system, including 5 first-layer factors, 10 second-layer factors, and 27 potential failure modes. The assessment index system almost contains the whole process of supply chain and provides the corresponding potential failure modes, and it can enhance the operability of the assessment work.

(2) To solve the two shortcomings of traditional FMEA, we provide an improved FMEA that combined with gray correlation and fuzzy theory. In the improved FMEA, the weights consider every layer factor's correlation. Also we introduce the gray relational degree to rank which makes the scoring more scientific and reliable.

(3) In order to test applicability of the improved FMEA model, we choose a shipbuilding Yard that is called RS to study. The results showed that vulnerability is mainly concentrated on the manufacturing, procurement, excess capacity, and other links. We make some proposals to make vulnerability identification and assessment, which might be helpful for the similar shipbuilding enterprise.

(4) In order to verify the effect of the improved FMEA, the paper used Kendall's tau coefficient to assess the ten scoring methods, only fuzzy theory FMEA, and improved FMEA. The study found that the improved FMEA method is the best in isotonicity, which means that the improved FMEA method is more in line with reality.

Disclosure

The draft of this paper has been presented in 2014 International Joint Conference on Computational Sciences and Optimization [30].

Competing Interests

The authors declare that they have no competing interests.

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Research Article

Modeling the City Distribution System Reliability with Bayesian Networks to Identify Influence Factors

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Under the increasingly uncertain economic environment, the research on the reliability of urban distribution system has great practical significance for the integration of logistics and supply chain resources. This paper summarizes the factors that affect the city logistics distribution system. Starting from the research of factors that influence the reliability of city distribution system, further construction of city distribution system reliability influence model is built based on Bayesian networks. The complex problem is simplified by using the sub-Bayesian network, and an example is analyzed. In the calculation process, we combined the traditional Bayesian algorithm and the Expectation Maximization (EM) algorithm, which made the Bayesian model able to lay a more accurate foundation. The results show that the Bayesian network can accurately reflect the dynamic relationship among the factors affecting the reliability of urban distribution system. Moreover, by changing the prior probability of the node of the cause, the correlation degree between the variables that affect the successful distribution can be calculated. The results have significant practical significance on improving the quality of distribution, the level of distribution, and the efficiency of enterprises.

1. Introduction

With the ups and downs of economic development in recent years, urbanization is speeding up, cities are being expanded, and the urban population has been dramatically increased, which leads to an increasing complexity of business environment such as diversity, uncertainty, and instability of market. With this situation, the research on reliability of urban distribution system is becoming important and has a practical significance to integrate logistics and supply chain resources, to further improve the national economy with a sustained, healthy, and rapid development.

The level of reliability on urban distribution not only reflects the capacity of the various unit components in distribution system to contact and coordinate each other, but also reflects the ability to guarantee a rapid, stable, and sustainable development environment for society and economy. Urban distribution is sensitive in both internal and external development process, which makes it becoming more easily disturbed and affects its reliability.

Bayesian network is a graphic model that combines graph theory and probability theory in the field of artificial intelligence. It can simulate the causal relationships among different subjects in the real world and also well combine prior knowledge and posterior data. Bayesian network is an important application on dealing with uncertain information, and it has been successfully used in several areas such as medical diagnosis, statistical decision, and learning prediction. In this paper, we use Bayesian networks to deeply analyze the influence factors of the reliability in city distribution system. Parameter learning of Bayesian network is mainly based on the existing training data. But in real world, there is little complete data for learning. EM algorithm is an algorithm for parameter, which can improve the accuracy of network parameters. So we combine Bayesian network and EM algorithm to make the calculated value more exact.

The remainder of this paper is organized as follows. Section 2 provides the relevant literature on urban distribution, urban distribution system reliability, and Bayesian networks. Section 3 describes the factors affecting the reliability of

urban distribution system. Section 4 presents model of urban distribution system reliability factors based on Bayesian network. In Section 5, a numerical study of different cases is presented. Section 6 comes up with conclusion of the study.

2. Literature Review

Reliability research is widely used in many fields, but the research in the logistics system is only emerged gradually in recent years. At present, there are already some domestic and foreign scholars on the reliability of the logistics system study. The research results from the supply chain reliability can be used for the reliability of logistics system research route, methods and tools, and so forth.

Thomas [1] first used reliability engineering in the study on supply chain and gave the probability model of the supply chain reliability in emergency environment, but it does not involve the logistics operation details. In order to ensure the normal operation of the supply chain, Chen and Xue [2] build a comprehensive evaluation model of reliability of supply chain based on MAS (Mobile Agent Server). City logistics system is a complex network system; some scholars have conducted research on the reliability of city logistics network from the perspective of the reliability of complex networks. Tran and Zhiya [3] measured shortage of client in the logistics system and defined the logistics network point of supply reliability, arc reliability, and logistics network reliability from the viewpoint of probability. They construct a single-layer network reliability model. Then they put forward the reliability of the logistics network optimization problem and constructed a double objective chance constrained programming model based on service reliability and cost. To measure the logistics system reliability, Lin [4] proposed a model and method to measure the operation performance of the network and the reliability of network structure when the logistics network node malfunctions. Schuëller et al. [5] qualitatively discussed the reliability of the logistics system and the metrics and methods of some other logistics property which influence the logistics system reliability, but not for the quantitative research of strict. Wang et al. [6] defined the reliability of logistics service as a function of the distance and put forward a modeling method of the logistics service reliability. Križman [7] studied measure method and the convergent validity algorithm of the logistics structural reliability. Xu et al. [8] proposed a bilevel programming model which can reduce or eliminate the adverse effects of supply uncertainty in collaborative logistics network (CLN) resource matching process. By adding the robust constraints, this model reduces both the frequency and the cost of resource planning changes, which lead to increasing stability of CLN operation. In the field of logistics system reliability research, the existing literature research focuses on logistics system reliability measure, evaluation, and prediction, mainly using the Monte Carlo, the fault tree, and probability analysis method to establish the assessment model of logistics system reliability and obtained certain research results. From the research tendency, the research on the reliability of logistics system will be more specific, such as the problem of reliability level and influence factors. Moreover, research on the reliability of logistics systems will be more closely combined with the key technology problem which needs to be solved urgently in the national economy and social development, and the application value will become more and more obvious.

Bayesian network is a methodology that has been widely used in fault diagnosis, reliability analysis, economic forecasting, and so forth. Since 2001, the application of Bayesian network is expanded to risk analysis by Weber et al. [9]. For example, Norrington et al. [10] studied the network construction procedures intensively to improve the reliability of risk analysis. By applying the probability inference theory to the network topology, Bayesian network can be used to identify the most influential factors by Hänninen and Kujala [11]. Now Bayesian network has been applied in the research of the logistics system. Tian-kui et al. [12] put forward a fuzzy comprehensive evaluation of supply chain risks based on Bayesian networks. Taking the supply chain risks of an enterprise as an example, they calculated the logarithmic probability P of risky affairs through linear deduction of Bayesian networks and then worked out the main risky affairs and their ranks by the way of fuzzy comprehensive evaluation. Li et al. [13] establish a local risk analysis model of food supply chain based on the Bayesian network, which can predict the risk. Wen-Fang [14] analyzed the key factors affecting the evaluation of logistics performance and their relationship with each other through analyzing the connotation of logistics performance evaluation. And the evaluation index system of logistics performance is constructed from the logistics service quality performance, logistics strategy and system, and operation service and supporting. Guo et al. [15] crystallized the abstract problem of cold-chain logistics system fault and constructed fault tree according to operation features of various functional parts and the causal relationship between events in cold-chain logistics system. By converting fault tree to Bayesian networks, it is convenient to draw a comprehensive evaluation for the system reliability of cold-chain logistics system and reveal the main cause of system failure, in order to provide quantitative foundation for improving system reliability. As can be seen from these results, the use of Bayesian networks is extremely broad, but the use is not widespread in the field of the reliability of logistics system. This paper applied the method to study the factors affecting urban logistics distribution system reliability to analyze the impact of these factors on system reliability.

EM algorithm proposed in 1977 by Dempster et al. [16] is an iterative maximum likelihood estimation of the optimization strategy for seeking parameters. It can focus on the noncomplete data from the parameters of maximum likelihood estimation. This method can be widely used in missing data, incomplete data, and censored data with noise. Some scholars combine the EM algorithm and the Bayesian network to solve the problem. Liu and He [17] apply the Naive Bayesian Method and the EM algorithm in Chinese web-page classification, which improves the final convergent result by continually changing the convergent initial conditions. Wang et al. [18] proposed a method that combines data revising and the Bayesian structural EM algorithm, which is effective

in learning Bayesian networks from small data set. Wei and Huijin [19] use the result of Naive Bayesian as the initial range of EM, then refine the value reduplicate, and finally get the excepted maximized value. Cao et al. [20] propose a learning algorithm based on cloud model and EM algorithm to solve the problem that the conception of node which has been discrete is fuzzy and random in Bayesian network. These papers focus on theoretical research. In this paper, the EM algorithm and Bayesian network are combined to study the influence factors of urban distribution system reliability.

3. Analysis of the Key Influence Factors of City Logistics Distribution System

In this paper, four influence factors will be discussed. They are hardware configuration, personnel operation, external factors, and the change of customer demand.

3.1. Hardware Configuration. For hardware configuration, there are facilities, logistics technology, and information systems.

Facility is one of the most important elements of logistics systems, which undertakes various tasks of logistics operation of each link, which is in a very important position in the logistics system. Logistics facilities include logistics packaging, warehouse, storage, transportation, loading and unloading handling, container utilization, and port logistics and distribution facilities in the process of machining. Advanced logistics facilities and equipment are a guarantee of efficiency, high-quality, and low-cost logistics operation. Thus logistics distribution system efficiency will be extremely low without the logistics equipment.

Logistics technology includes some basic technology and methods such as logistics prediction, supplier selection, inventory control, and logistics packaging. The content of the logistics industry has been changed with each passing day, so the new concept and technology of logistics play a vital role in the development of logistics industry. In twenty-first century, some theories of logistics and technology such as "frontier logistics," "6 Sigma Logistics," "closed loop logistics and reverse logistics," and "RFID" have greatly promoted the development of the logistics industry. But in the meantime, they brought us more challenges and uncertainties to the city distribution system.

The flow of goods is accompanied by the flow of information, and information plays an important role in city logistics system. In China, there is no unified platform in logistics information, which directly leads to a low degree of information sharing between various enterprises. On the one hand, because of the difficulty in the communication of information, once there are some problems arising, the error information will be difficult to correct, which will significantly affect the reliability of logistics distribution system. On the other hand, due to the lack of a unified system of standardization, the information is difficult to transmit within different enterprises, which eventually weaken the function of information system.

3.2. Personnel Operating Factors. Personnel operating factor refers to the uncertainty of the system caused by the specific operational problems. It includes stocking process, process storage, and the quality of delivery staff.

Stock is the basic work in distribution, which mainly includes the order, purchase, goods collection, purchasing, and other related processes. Stock is a key link to the success of distribution, which is also one of the important factors that affect the city logistics distribution system reliability. Any personnel information input, wrong label posts, and scanning errors would delay the delivery of goods.

Storage is a guarantee to meet customer demand and to deal with emergency and also an important part to ensure the reliability of urban logistics distribution system. Storage should be processed in a planned way based on past experience and customer orders. The hoarding of goods will not only extend the cash cycle but also may cause some risks for quick replacement of products.

The quality of delivery staffs directly affects the goods delivery rate and customer satisfaction. The distribution industry management has some requirements. (1) Timeliness: is the delivery in the stipulated time? (2) Safety: whether the goods are damaged or lost? Some products need unpacking inspection of their quality and quantity by customers (service quality). The attitude of delivery staff may significantly determine customers satisfaction. Operation mainly includes the waybill filled and the packaging completed.

3.3. External Factors. External factors refer to the external factors of city logistics distribution system including government policy factors, emergency, macroeconomic fluctuations, and the international factors.

In China, the government's policy is of great significance for the development of logistics, and the change of government policy will have a significant influence on the development of logistics industry, while it cannot be denied that there are still some defects of Chinese government functions in the process of city logistics development, which mainly include the defects of government's logistics management system, the government's lack of guidance of modern logistics, and the weakness of government's regulation of logistics market. Hence, the development of city logistics needs the establishment of the urban infrastructure system, the improvement of enterprise logistics network, the construction of logistics system and logistics standardization, and a good environment for enterprise development. The unpredictability of government policy has brought a series of uncertainty, which will directly affect the reliability of the urban logistics system.

The State Council issued "overall national public emergency contingency plan," which mentions that public emergency events may cause heavy casualties, property damage, environmental damage, serious social harm, and public safety problems. Public emergency has the characteristics of suddenness, complexity, destructiveness, and continuity. Many sudden natural disasters can interrupt logistics operation process and influence the normal function of urban logistics flow and functions. Therefore, the public emergency

is an important factor for the uncertainty of city logistics distribution system.

City logistics distribution system is a complex economic system in terms of the mutual influence and mutual restriction within the whole national economy. First of all, city logistics economy is an important component of the national economy systems. On the one hand, its development will promote national economy. On the other hand, the development of the national economy also has a significant influence on the development of city logistics. And macroeconomic fluctuations have a great impact on city logistics system. When the macroeconomics is overheated, logistics economy will be booming, and even there is an expansion trend. And when macroeconomics declines, the city logistics demand will decrease and the investment will be greatly reduced as well.

With the development of economic globalization, the connection between the Chinese economy and world economy is gradually strengthened especially after China's accession to the WTO (World Trade Organization), which brings us the opportunities and challenges simultaneously. Enterprises have been facing the pressure from both domestic and overseas competition. Foreign logistics enterprises moving into our country become a challenge for the development of domestic enterprises. In the same time, the connection between the countries became closer than ever before. A country's economic fluctuation will also have impact on other countries' economic development, which brings a series of uncertainty to city economy.

3.4. Customer Demand. From the customers' requirement perspective, the frequent changes of orders from customers and the irregularities of orders have an impact on demand forecasting. In shorter production cycle of enterprise, the change of demand forecasting leads to corresponding changes of production plan, procurement, and scheduling. For the longer production cycle of enterprise, the change is unable to meet the final demand of the customers, as it cannot change the production plan. The uncertainty of demand mainly comes from the incorrect forecast method, decision error, and variability of customer demand.

4. Bayesian Network Construction

4.1. Basic Principle of the Bayesian Network. Bayesian network is a graph theory model, which is established based on the relationship between probabilities of random variables and represented by directed cyclic graph (DAG). It has two elements: nodes and arcs. Node is the basis of Bayesian network structure, which represents the basic elements of Bayesian network modeling events. A directed arc between the nodes indicates that the condition dependency results from the cause node to final node. Bayesian network can be expressed by the following mathematical expression: DAG = (P, L), $P = (p_1, p_2, \ldots, p_i)$, $L = (l_1, l_2, \ldots, l_i)$, and P and L represent nodes and directed arcs in the Bayesian network. A simple Bayesian network is shown in Figure 1.

In Figure 1, A, B, and C represent individual node, and the variable to each node should be expressed by lower case letters. For example, the variable of node A is expressed as $a_1, a_2, \ldots, a_i$ and satisfies $P(a_1) + P(a_2) + \cdots + P(a_i) = 1$, and in the same way, we can have the variable that represents nodes B, C.

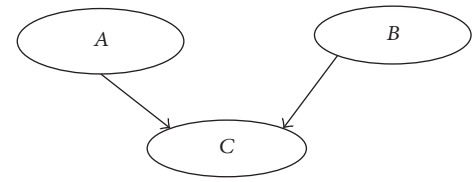

Figure 1: Simple Bayesian network diagram.

Assuming the existence of $X_1, X_2, \ldots, X_i$ in a Bayesian network, there are as many as i independent nodes:

$$P(X_1 X_2 \cdots X_i) = P(X_1) P(X_2) \cdots P(X_i). \tag{1}$$

According to formula (1) and Byes theorem, the joint and conditional probability is

$$P(X_1 X_2 \cdots X_i) = P(X_1) P(X_2 \mid X_1) P(X_3 \mid X_1 X_2) \cdots P(X_i \mid X_1 X_2 \cdots X_{i-1}). \tag{2}$$

Formula (2) can be further expressed as

$$P(X_1 X_2 \cdots X_i) = \prod P\left(X_i \mid \prod (X_i)\right). \tag{3}$$

$\prod(X_i)$ can be called the parent node of X_i, in the Bayesian network, if the directed arcs connect node X with Y and point from node X to Y, and we call X the parent node to Y and Y is a child node to X. If X_i has no parent node, we call it the root node.

Total probability formula is as follows.

Sample E provided the experimental space S, A is an event of E, $B_1, B_2, \ldots, B_n$ is a partition of S, and $P(B_i) > 0$ $(i = 1, 2, \ldots, n)$.

Then,

$$P(A) = P(A \mid B_1) \times P(B_1) + P(A \mid B_2) \times P(B_2) + \cdots + P(A \mid B_n) \times P(B_n). \tag{4}$$

A Bayesian network is a kind of probabilistic reasoning algorithms based on the relationship between the nodes variables in a Bayesian network. In practical applications, the specific structures of the Bayesian network are rather complex, and the probabilistic reasoning for the whole Bayesian network could be relatively difficult and tedious, as the network between adjacent nodes is assumed to be nonindependent, so we can define a node as an intermediate node, and the node can form a sub-Bayesian network with its child nodes and parent nodes. In this way, a complex Bayesian network can be decomposed into a number of simple "sub-Bayesian networks," through the probabilistic reasoning to the "child Bayesian network," and it could figure out the conditional probability of whole Bayesian network. We firstly set the prior probability of Bayesian network, and directed

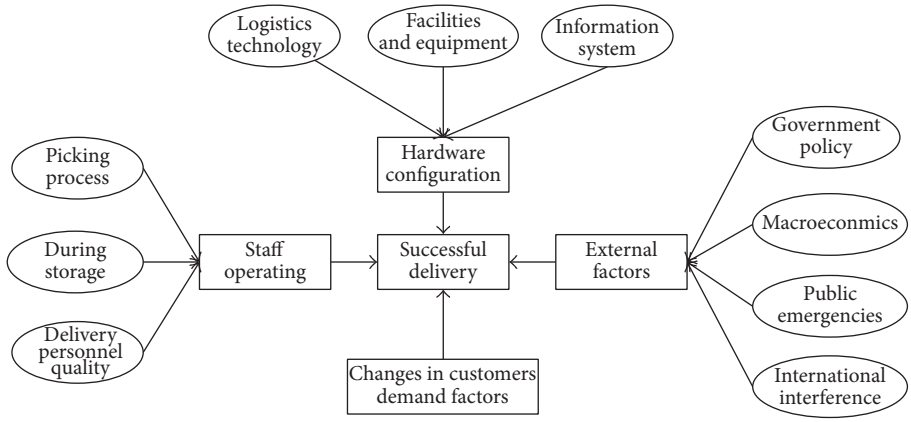

Figure 2: Urban distribution system reliability factors model.

arcs represent the relationship between the nodes, using the basic principles of probability theory, and the probabilistic reasoning between networks nodes could reflect the impact degree of the cause node to the result node. Therefore, we can calculate the probability of the relationship nodes in different structure according to the different needs and then reflect the relationship between the nodes.

4.2. Parameter Learning. Parameter learning of Bayesian network is mainly based on the existing training data. But in real world, there is little complete data for learning. Therefore, to improve the accuracy of network parameters, modifications based on mathematical method are essential. Here, Expectation Maximization algorithm is applied (Kjærulff and Madsen [21]). As an algorithm for parameter adjustment, it can be used to maximize the likelihood estimation with incomplete data. By iterating the expectation step and maximization step, the EM algorithm can repair missing data and refine it gradually until the data likelihood value reaches a local optimal. In the expectation step, the likelihood function of the current parameter θ is expected when the set of samples D is given; in the maximization step, the likelihood function obtained at the expected stage is maximized. And replace the next expectation with the maximized result, and then perform the desired calculation. The EM algorithm repeats steps E and M until the expected error in the estimate is less than a fixed limit. EM algorithm for the parameter estimation provides a reliable method, which is considered the most feasible solution to the current data loss method. The specific algorithm steps are as follows.

Given the Bayesian network structure S, the incomplete data variable set X is as follows: $X = \{X_1, X_2, \ldots, X_n\}$, and X_1 is the first incomplete data variable set; $D = \{D_1, D_2, \ldots, D_n\}$ is the complete data set, $D \in X$.

Step 1 (expectation step). Consider

$$\begin{aligned} N_{ijk}^t &= \left[N_{ijk} \mid X, \theta, S\right] \\ &= \sum_{1}^{N} p\left(v_i = k,\ \mathrm{pa}\left(v_i\right) = j \mid X, \theta, S\right), \end{aligned} \tag{5}$$

where θ is the parameter to be estimated, v_i is the child node i, $i = (1, 2, 3, \ldots, k)$, $\mathrm{pa}(v_i)$ is the parent node of v_i, $\mathrm{pa}(v_i) = \{1, 2, 3, \ldots, j\}$, and N_{ijk} is the count of $(v_i, \mathrm{pa}(v_i)) = (k, j)$. The E-step of the EM algorithm is to calculate the expected sufficient statistics for a complete database.

Step 2 (maximization step). Consider

$$\begin{aligned} \theta^t &= \arg\max_{\theta^t} Q\left(\theta^t \mid \theta\right) \\ &= \arg\max_{\theta^t} E\left[p\left(D \mid \theta\right) \mid X, \theta^t, S\right] = \frac{N_{ijk}^t}{\sum_{i=1}^{\|v_i\|} N_{ijk}^t}, \end{aligned} \tag{6}$$

where θ^t is the new parameter. The maximization step is to compute the maximum likelihood estimate of θ^t, expressed by N_{ijk}.

5. Case Analysis

5.1. Model of Reliability Factors in Urban Distribution System. According to the analysis of the reliability factors in urban distribution system in Section 4, we give the model of reliability factors in urban distribution system in this section, as shown in Figure 2.

5.2. Sub-Bayesian Network Inference. In order to facilitate the analysis, we decompose the Bayesian network of urban distribution system reliability factors into several simple "sub-Bayesian network reasoning." We select a "sub-Bayesian network" in Figure 2 for calculation. In the "sub-Bayesian network," the hardware configuration for the intermediate nodes, logistics technology, facilities and information system for the parent node, and successful distribution for the child nodes are shown in Figure 3.

In the Bayesian network, we get the initial measurement data from a logistics company. We did a sample survey and set the number of samples as 50. Table 1 shows the survey results. Then we analyze the data and get the prior probability of cause variables. For factors such as human and organizational factor, the statistical data are not sufficient. Thus, the EM

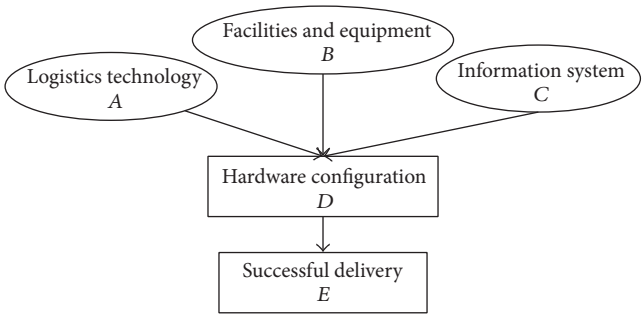

Figure 3: Child Bayesian network of urban distribution system reliability factors model topology.

algorithm and experts experience are essential. When there is some data missing in the numerical statistics results, first calculate the parameters according to the existing data. Then the estimated value of the first iteration is calculated according to formulas (5) and (6). Repeat expectation step and maximization step, until the error between the first and last iteration values is less than 0.005 when the iteration is stopped. At this time, we get more accurate results. With the EM algorithm, the Bayesian model can lay a more accurate foundation for the relations and dependencies between incidents.

In the example, we firstly set the parent node according to the prior probability of the data, as shown in Table 2. Among them, A means that the logistics technology is suitable for the operation of logistics enterprises; $\overline{A}$ means that the logistics technology is not suitable for the operation of logistics enterprises; B means that equipment is in good condition; $\overline{B}$ means that equipment is not in good condition; C means that the use of information systems will improve the operational efficiency; $\overline{C}$ means that the use of information systems will not improve the operational efficiency; D means that hardware configuration system functions correctly; $\overline{D}$ means that hardware configuration system cannot function correctly. E means that the entire distribution process is successful, and $\overline{E}$ means that distribution process is unsuccessful.

$ABCD$ represent four conditions that are established and so on. Tables 3 and 4 show the joint probability between various factors.

According to formula (3) and total probability formula (4), we can calculate the probability for D:

$$\begin{aligned} P(D) = {} & P(ABC) \times P(D \mid ABC) + P\left(A\overline{B}C\right) \\ & \times P\left(D \mid A\overline{B}C\right) + P\left(AB\overline{C}\right) \times P\left(D \mid AB\overline{C}\right) \\ & + P\left(\overline{A}BC\right) \times P\left(D \mid \overline{A}BC\right) + P\left(\overline{A}\,\overline{B}C\right) \\ & \times P\left(D \mid \overline{A}\,\overline{B}C\right) + P\left(\overline{A}B\overline{C}\right) \times P\left(D \mid \overline{A}B\overline{C}\right) \\ & + P\left(A\overline{B}\,\overline{C}\right) \times P\left(D \mid A\overline{B}\,\overline{C}\right) + P\left(\overline{A}\,\overline{B}\,\overline{C}\right) \\ & \times P\left(D \mid \overline{A}\,\overline{B}\,\overline{C}\right) = 0.8578. \end{aligned} \tag{7}$$

Table 1: The measurement data.

Number	Date	Logistics technology	Facilities and equipment	Information system
1	2013/9/1	√	√	√
2	2013/9/8	√	√	√
3	2013/9/15	×	×	√
4	2013/9/22	√	√	√
5	2013/10/1	×	√	×
6	2013/10/8	√	√	√
7	2013/10/15	√	√	√
8	2013/10/22	√	√	√
9	2013/11/1	√	√	√
10	2013/11/8	√	√	√
11	2013/11/15	√	×	×
12	2013/11/22	√	√	√
13	2013/12/1	√	√	√
14	2013/12/8	√	√	√
15	2013/12/15	√	√	√
16	2013/12/22	√	√	√
17	2014/1/1	√	×	√
18	2014/1/8	√	×	√
19	2014/1/15	√	√	√
20	2014/1/22	×	√	√
21	2014/2/1	√	√	√
22	2014/2/8	√	√	√
23	2014/2/15	√	√	√
24	2014/2/22	√	√	√
25	2014/3/1	√	√	√
26	2014/3/8	×	√	√
27	2014/3/15	√	×	×
28	2014/3/22	√	√	√
29	2014/4/1	√	√	√
30	2014/4/8	√	√	√
31	2014/4/15	√	×	√
32	2014/4/22	√	√	√
33	2014/5/1	√	√	×
34	2014/5/8	√	√	√
35	2014/5/15	√	√	√
36	2014/5/22	√	×	√
37	2014/6/1	√	√	√
38	2014/6/8	×	√	√
39	2014/6/15	√	√	√
40	2014/6/22	√	×	√
41	2014/7/1	√	√	√
42	2014/7/8	√	√	√
43	2014/7/15	√	√	×
44	2014/7/22	√	√	√
45	2014/8/1	√	√	√
46	2014/8/8	√	×	√
47	2014/8/15	√	√	√
48	2014/8/22	√	√	√
49	2014/9/1	√	×	√
50	2014/9/8	√	√	√
Total number of failures		5	10	5

Table 2: Parent prior probability.

Probability	A	$\overline{A}$	B	$\overline{B}$	C	$\overline{C}$
P	0.9	0.1	0.8	0.2	0.9	0.1

Table 3: Joint probability between the hardware configuration and its parent.

Joint conditional probability	ABC	$A\overline{B}C$	$AB\overline{C}$	$\overline{A}BC$	$\overline{A}\,\overline{B}C$	$\overline{A}B\overline{C}$	$A\overline{B}\,\overline{C}$	$\overline{A}\,\overline{B}\,\overline{C}$
D	0.99	0.63	0.67	0.72	0.41	0.37	0.21	0.02
$\overline{D}$	0.01	0.37	0.33	0.28	0.59	0.63	0.79	0.98

Table 4: Joint probability between hardware configuration and successful distribution.

Joint conditional probability	D	$\overline{D}$
E	0.82	0.11
$\overline{E}$	0.18	0.89

Further we can derive the conditional probability E:

$$P(E) = P(D) \times P(E \mid D) + P\left(\overline{D}\right) \times P\left(E \mid \overline{D}\right) = 0.7191. \tag{8}$$

5.3. Internode Correlation Calculation according to the Change of Prior Probability. In Bayesian network probabilistic reasoning, we define the degree of interaction between nodes of the association degree. (We use "R" in this paper.) The correlation of Bayesian network after the change of node prior probability can be represented by the following formula:

$$R = \frac{\Delta P(j)/P(j)}{\Delta P(i)/P(i)}. \tag{9}$$

Among them, $\Delta P(i)$ means the variation of parent node i probability and $\Delta P(j)$ means the variation of child node j probability, and then we change the prior probability of parent node A as $P'(A) = 0.6$ and keep the initial state of B and C. Similarly, we can deduce the probabilities of nodes D and E: $P'(D) = 0.77928$, $P'(E) = 0.66329$.

According to formula (9), we can calculate the correlation between the logistics technology and equipment of the hardware, and also the correlation between the logistics technology and the successful distribution:

$$R = \frac{\Delta P(D)/P(D)}{\Delta P(A)/P(A)} = 0.2747, \qquad R = \frac{\Delta P(E)/P(E)}{\Delta P(A)/P(A)} = 0.2327. \tag{10}$$

Similarly, we can calculate the situation when changing the prior probability of a parent node for B, $P'(B) = 0.6$, the correlation between the facilities and equipment of the hardware, and also the correlation between the facilities and the successful distribution:

$$R = \frac{\Delta P(D)/P(D)}{\Delta P(B)/P(B)} = 0.3398, \qquad R = \frac{\Delta P(E)/P(E)}{\Delta P(B)/P(B)} = 0.2879. \tag{11}$$

When the prior probability of parent node C changes as $P'(C) = 0.6$, the correlation between the information system and equipment of the hardware and also the correlation between the information system and the successful distribution are

$$R = \frac{\Delta P(D)/P(D)}{\Delta P(C)/P(C)} = 0.3586, \qquad R = \frac{\Delta P(E)/P(E)}{\Delta P(C)/P(C)} = 0.3037. \tag{12}$$

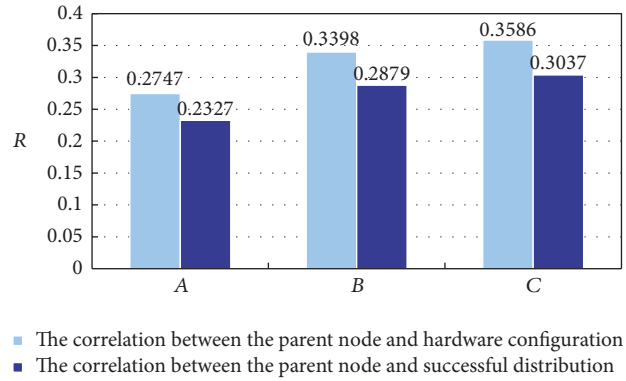

Figure 4: The association degree.

The result is given in Figure 4. It can be seen from Figure 4 that the correlation among the information system, the equipment of the hardware, and the successful distribution is in max degree. The information system has a great effect on the equipment of the hardware, and it also plays an important role in the successful distribution. Therefore, we propose that, in daily operation, distribution enterprises should pay attention to the daily maintenance work of information system and hire professionals to ensure the normal operation of the information system. The correlation among information system, the equipment of the hardware, and the successful distribution is large. So enterprises should increase the equipment investment. In order to promote the development of logistics industry, the government should take the responsibility of management functions, strengthen the investment in infrastructure, and create a good environment, which will provide a solid foundation for the development of distribution business. The correlation among the logistics technology, the equipment of the hardware, and the successful distribution is min, even though we cannot ignore.

5.4. The Probabilities of the Nodes Change Rate Calculation When Conditional Probability Changes. In the Bayesian network probabilistic reasoning, we can simulate that the various factors on the changes of distribution affect the degree of success in specific environment through the internode conditional probability change. In this paper, the change of conditional probability between the hardware facilities and successful distribution is analyzed as an example. We assume that, with changes in the external environment, the joint probabilities between the hardware facilities and successful distribution decrease from 0.82 to 0.7, and when other probability conditions are not changed, the probability of node E is calculated as D: $P'(E) = 0.6161$, and the results above show $P(E) = 0.7191$. Therefore, successful delivery rate of change is

$$\text{ROC} = \frac{\Delta P(E)}{P(E)} \times 100\% = 14.32\%. \tag{13}$$

When the conditional probability of hardware facilities and the successful distribution change, $P(E \mid D)$ get changed from 0.82 to 0.7, and the successful distribution will fall 14.32%. Similarly, we could also calculate the changes of factors affecting the probability distribution of each node to other nodes which change under the conditional probability.

6. Conclusions

The research results and the contribution of this article are as follows.

First of all, according to the feature of Bayesian network structure, a complex Bayesian network can be divided into several simple sub-Bayesian networks by selecting the appropriate intermediate node, which can reduce the computational difficulty. This paper illustrates this point with an example.

When analyzing factors on the reliability of city distribution system using Bayesian network, the correlation factors of the variables and the successful delivery can be calculated by changing the prior probability of parent node, and through the analysis of the correlation degree of each node, the degree of influence of each factor on the success of distribution can be inferred.

With the development of science and technology, the influence factors of the city distribution system and the relationship between all the influence factors are constantly changing, by adjusting the conditional probability of variables, and the dynamic change process of the relationship among variables can be reflected more truly. With the change of environment, the conditional probability of each variable will be changed accordingly, and the influence of variables on the reliability of distribution system will be different. Therefore, this method can be used to measure the change of the probability of the conditional probability between nodes. Using the results of the study, distribution enterprises can calculate the impact of various factors on the distribution system reliability, identify the key factors, and improve them based on the actual operation of the company.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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Research Article

Supply Chain Network Design under Demand Uncertainty and Supply Disruptions: A Distributionally Robust Optimization Approach

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We develop a robust optimization model for designing a three-echelon supply chain network that consists of manufacturers, distribution centers, and retailers under both demand uncertainty and supply disruptions. The market demands are assumed to be random variables with known distribution and the supply disruptions caused by some of the facilities faults or connection links interruptions are formulated by several scenarios with unknown occurrence probabilities. In particular, we assume the probabilities that the disruption scenarios happen belong to the two predefined uncertainty sets, named box and ellipsoid uncertainty sets, respectively. Through mathematical deductions, the proposed robust SCN design models can be transformed into the tractable linear program for box uncertainty and into second-order cone program for ellipsoid uncertainty. We further offer propositions with proof to show the equivalence of the transformed problems with the original ones. The applications of the proposed models together with solution approaches are investigated in a real case to design a tea supply chain network and validate their effectiveness. Numerical results obtained from model implementation and sensitivity analysis arrive at important practical insights.

1. Introduction

Designing and managing a supply chain network have become crucial due to the increasing market competition, variable customer demands, and the fast development of the economic and technological globalization. An efficient supply chain network will contribute to quickly responding to the customers' demands and achieving the success of the supply chain which depends on the cooperation and coordination among all members. Supply chain network (SCN) design incorporates both strategic and tactical decisions on the number, location, capacity, and mission of the supply, production, and distribution facilities required to provide goods to a customer base [1]. In recent years, lots of mathematical models have been developed to solve various supply chain network design problems. A. Nagurney and L. S. Nagurney [2] consider a firm that is engaged in determining the capacities of its various supply chain activities and develop a rigorous modelling and analytical framework for the design of sustainable supply chain networks. Bashiri et al. [3] present a mathematical model for strategic and tactical planning in a multiple-echelon, multiple-commodity production-distribution network. Mahdi et al. [4] indicate the SCN design can significantly affect the economic viability of a biofuel technology and develop a mixed-integer linear programming to determine the optimal supply chain design and operation under uncertain environment. Jeihoonian et al. [5] adopt a mixed-integer programming model to design a closed-loop supply chain network for durable goods and coordinate forward flow and reverse flow to determine the position of each type of facilities in the entire network. For comprehensive reviews of SCN design models, see Klibi et al. [6], Tokman and Beitelspacher [7], and Farahani et al. [8].

By investigating the supply chain models, Melo et al. [9] find that both strategic and tactical decisions can be highly affected by various sources of uncertainty such as demand and supply interruptions, lead time variability, exchange rate volatility, and capacity variations [10]. From the perspective

of risk management, Tang [11] defines two categories of risks in supply chains. One is operational risks arising from business-as-usual incidents, such as machine breakdowns and power outages which lead to uncertainties in matching supply and demand. The second category is disruption risks, which arise from natural and man-made disasters such as earthquakes, floods, hurricanes, and terrorist attacks. Operational risks are usually captured through incorporating such inherent uncertainties in the input data such as uncertain customer demand, uncertain supply capacity, and uncertain costs due to dynamic and fluctuating nature of these parameters. Disruption risks are usually captured by incorporating disruption scenarios in the model formulation of underlying decision problem since they are unlikely to occur but have a high impact when they do occur [12]. To cope with the disadvantage effect of the uncertainties on supply chain operations, Klibi et al. [6] suggest that stochastic programming can be used as a powerful technique to tackle uncertainties. Furthermore, a so-called scenario-based stochastic programming has been paid more attention in SCN design problems. Scenario-based stochastic programming optimizes the expected value of the objective functions by considering a set of discrete scenarios and their occurrence probabilities for random variables. Following such logic, Mulvey et al. [13] initially propose a scenario-based robust stochastic optimization for large-scale systems and define two measures of robustness, namely, model robustness and solution robustness, respectively. A solution to an optimization model is defined as robust solution if it remains close to optimal for all scenarios of the input data and robust model if it remains almost feasible for all data scenarios. By using a parameter reflecting the decision-maker's preference between the solution and model robustness, it incorporates the conflicting objectives of the two. The scenario-based robust optimization can be regarded as a two-stage stochastic programming in essence and has been adopted as an effective tool for designing and managing the supply chain operating in uncertain environments.

Using the robust optimization approach proposed by Mulvey et al. [13], Babazadeh and Razmi [14] develop an efficient mixed-integer linear programming to handle both operational and disruption risks of the agile supply chain network. Baghalian et al. [15] consider both demand-side and supply-side uncertainties and develop a stochastic mathematical formulation for designing a network of multiproduct supply chains. Jabbarzadeh et al. [16] present a dynamic supply chain network design model for the supply of blood during and after disasters which can assist in blood facility location and allocation decisions for multiple postdisaster periods. Jeong et al. [17] provide an integrated framework to design emergency logistics networks comprising distribution warehouses, disaster recovery centers, and neighbourhood locations based on efficiency, risk, and robustness metrics, where the efficiency and risk are determined using transportation cost and relief item loss cost, while the robustness is analyzed in terms of perturbed transportation cost through diverse damage scenarios to major facilities. Fattahi and Govindan [18] apply a two-stage stochastic program to address a multistage and multiperiod supply chain network design problem under stochastic and highly variable demands.

Applications of robust stochastic programming techniques for SCN design models are limited because of the shortage of historical data for fitting probability distributions for uncertain parameters [19]. According to Klibi et al. [6], stochastic programming techniques usually require the perfect information of probability distributions of random variables, such as the likelihood of an interruption occurrence and its magnitude of impact. Such historical data, especially for those rare events, is limited or nonexistent making it difficult or impossible to estimate the actual distribution of uncertain parameters [20]. A robust optimization approach which depends on the complete distributions of the random variables on no condition could be adopted to handle uncertain parameters. Soyster [21] was the first to introduce a robust optimization formulation with interval data uncertainty, which will lead to the overconservative solutions because the probability at which uncertain parameters reach their worst values is as low as that at which they reach their normal values. Subsequently, Ben-Tal and Nemirovski [22], Bertsimas and Sim [23], and Ben-Tal et al. [24, 25] reduce the conservation of Soyster's approach by well defining the uncertainty sets to which the uncertain parameters belong and can thus be applied to design the robust supply chain network. Pishvaee et al. [26] assume the demand and the returns of used products vary in a specified closed bounded box and propose a robust optimization model for handling the inherent uncertainty of input data in a closed-loop supply chain network design problem. Hasani et al. [19] propose a general comprehensive model for strategic closed-loop supply chain network design, in which the uncertainties of parameters such as demand and purchasing cost in the proposed model are handled via an interval robust optimization technique. Hatefi and Jolai [27] propose a robust and reliable model for an integrated forward-reverse logistics network design, which simultaneously takes uncertain parameters and facility disruptions into account. More recently, Hasani et al. [28] propose a robust optimization model based on the uncertainty budget concept to consider uncertain parameters in global supply chain network design. Akbari and Karimi [29] use the similar robust optimization approach to design a multiechelon, multiproduct, multiperiod supply chain network under process uncertainty. Hasani and Khosrojerdi [30] develop a mixed-integer, nonlinear model and consider six flexible and resilience strategies simultaneously in designing robust global supply chain networks under disruptions and uncertainties. In addition, they present an efficient parallel Taguchi-based memetic algorithm to solve the proposed model.

From the literatures mentioned above, it can be seen that the disruption issues have drawn attention in SCN design problems. However, both demand uncertainty and supply disruption are rarely considered simultaneously [15, 31], especially for the unknown disruption occurrence probability. In this paper, we develop a path-based three-echelon robust SCN design model under both demand and supply uncertainties. For the uncertain market demand, we assume, without the loss of generality, it is a random variable with

a known distribution such as normal distribution, which may lead to a nonlinear model. To improve the solving efficiency, a piecewise linearization method is applied to transform the nonlinear terms into the linear ones. For the supply uncertainty, we consider some supply disruption scenarios caused by the manufacturers' facilities faults or the path interruption between the supply chain nodes. In particular, we use two predefined uncertainty sets, named box and ellipsoid, respectively, to describe the unknown probabilities that the disruption scenarios happen, which motivates us to adopt the robust optimization to build the SCN design models. Furthermore, through mathematical operations, all formulated robust optimization models are transformed into tractable convex programs and can thus be solved efficiently.

The remainder of this paper is organized as follows. We briefly introduce the SCN design problem under demand uncertainty and supply disruption in Section 2 and then propose a SCN design model in Section 3. In Section 4, we proposed two robust SCN design models when the disruption scenarios probabilities are bounded in the box uncertainty set and ellipsoid uncertainty set, respectively. We further transform them into the tractable linear and second-order cone programs to solve. A case study is given in Section 5 to illustrate the proposed models and solutions and to confirm their effectiveness. In the last section, we summarize the paper and discuss future research directions.

2. Problem Description

In this paper, we focus on the SCN design of a three-echelon supply chain under both the demand uncertainty and supply disruptions. The supply chain involves some potential manufactures, distribution centers, and retailers located in some candidate locations of the markets. As the market terminals, the retailers are in charge of the selling and face uncertain market demands that are considered as random variables with known distribution. Before observing the market demands, retailers need to place orders from the upstream. The distribution centers integrate the orders from the retailers and pass them to the manufacturers. To achieve economies of scale, the manufactures are inclined to integrate the orders and then organize production or purchase from the outer suppliers. Once the goods are produced and ready for shipment, they will be transported to distribution centers by consolidation and then arranged for delivery to multiple destinations. To meet the requirement of each market, a cross-dock operation can be adopted in the distribution centers to replenish fast-moving store inventories.

Figure 1 depicts the basic network structure. We also use the concept of a path or route instead of defining flow variables among the nodes of the supply chain [15]. Thus, each link starting from a manufacturer, passing through a distribution center, and ending at a retailer can be regarded as a potential transportation route. We further consider disruption risks in supply chain which impose great impacts on the companies' performance. According to Azad et al. [32], sources of disruption risks can be segmented into two categories: random disruption risks which may occur at any

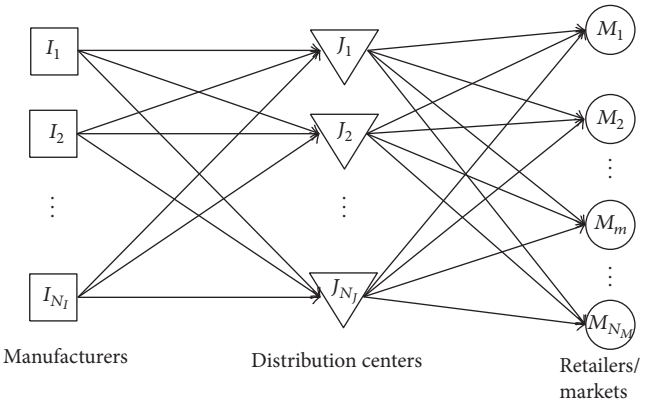

Figure 1: The three-echelon supply chain network.

physical point of supply chain network, for example, natural hazards and earthquakes, and premeditated disruption risks which are deliberately planned to inflict the supply chain with maximum damages.

In this paper, we mainly aim to explore the SCN design under premeditated disruption risks. In particular, we consider the supply disruptions due to the manufacturers' facilities impairments or connection links interruptions which result in some of the potential routes being unusable. The disruption set caused by a specific event is called a scenario and is assigned with a finite but unknown probability of occurrence, which is remarkably different from the literatures with the assumption of knowing the scenarios occurrence probability.

We propose a robust SCN design model incorporating both the demand uncertainty and supply disruptions to determine supply chain networks and operation strategies that can perform well under all scenarios. Two types of decision variables are considered in the proposed model. One involves numbers and locations of the distribution centers or retailers and is named the first-stage decision variables. The other concerns the product flow along the different routes and is named the second-stage decision variables. The former are used to determine the network structure, while the latter match with the operation strategies. Thus, the proposed robust SCN design models can be considered as two-stage robust optimization problems.

3. Mathematical Formulations

The sets, parameters, and variables used in the formulation of the robust SCN design model are defined in the Notations.

The expected profit of each market m in scenario s is given by

$$E[\pi_{sm}] = E\left[\sum_{p\in P} P_{mp}\cdot \min\left\{\sum_{r\in R^m} Q_{psr}, D_{mp}\right\}\right.$$

$$\left. + \sum_{p\in P} V_{mp}\cdot\left(\sum_{r\in R^m} Q_{psr} - D_{mp}\right)^{+} - \sum_{p\in P} C_{mp}\right.$$

$$\cdot \left(D_{mp} - \sum_{r \in R^m} Q_{psr} \right)^+ - \sum_{p \in P} \sum_{r \in R^m} H_{pr} \cdot Q_{psr} \Bigg]$$
$$= \sum_{p \in P} \left(P_{mp} + C_{mp} \right) \sum_{r \in R^m} Q_{psr}$$
$$- \sum_{p \in P} \left(P_{mp} + C_{mp} - V_{mp} \right) \int_0^{\sum_{r \in R^m} Q_{psr}} F\left(D_{mp} \right) dD_{mp}$$
$$- \sum_{p \in P} C_{mp} \cdot E\left[D_{mp} \right] \cdot \zeta_m - \sum_{p \in P} \sum_{r \in R^m} H_{pr} \cdot Q_{psr}, \tag{1}$$

where $x^+ = \max\{x, 0\}$ and $E[\cdot]$ represents the expectation operator. Note that the supply disruptions caused by the impairments of the manufacturer's facilities or the interruptions of the connection links are taken into account by defining several scenarios. In each scenario, some of the potential routes are unavailable. Therefore, the SCN design model incorporating the demand uncertainty and supply disruptions can be described as

$$\max \quad \Pi$$
$$= \sum_{s \in S} p_s \left(\sum_{m \in M} \sum_{p \in P} \left(P_{mp} + C_{mp} \right) \sum_{r \in R^m} Q_{psr} - \sum_{m \in M} \sum_{p \in P} \left(P_{mp} + C_{mp} - V_{mp} \right) \int_0^{\sum_{r \in R^m} Q_{psr}} F\left(D_{mp} \right) dD_{mp} - \sum_{m \in M} \sum_{p \in P} C_{mp} \right. \tag{2}$$
$$\left. \cdot E\left[D_{mp} \right] \cdot \zeta_m - \sum_{p \in P} \sum_{r \in R^m} H_{pr} \cdot Q_{psr} \right) - \sum_{j \in J} G_j \cdot \kappa_j - \sum_{m \in M} L_m \cdot \zeta_m$$

$$\text{s.t.} \quad \sum_{p \in P} Q_{psr} \le W \cdot B_{sr}, \quad \forall s \in S,\ r \in R, \tag{3}$$

$$\sum_{p \in P} \sum_{r \in R} Q_{psr} \le W \cdot \kappa_j, \quad \forall s \in S,\ j \in J, \tag{4}$$

$$\sum_{p \in P} \sum_{r \in R} Q_{psr} \le W \cdot \zeta_m, \quad \forall s \in S,\ m \in M, \tag{5}$$

$$\sum_{j \in J} G_j \cdot \kappa_j + \sum_{m \in M} L_m \cdot \zeta_m \le y, \tag{6}$$

$$\sum_{r \in R^i} Q_{psr} \le Q_{ip}^{\max}, \quad \forall i \in I,\ p \in P,\ s \in S, \tag{7}$$

$$Q_{psr} \ge 0, \quad \forall p \in P,\ s \in S,\ r \in R, \tag{8}$$

$$\kappa_j, \zeta_m \in \{0, 1\}, \quad \forall j \in J,\ m \in M. \tag{9}$$

Objective function (2) aims to maximize the whole supply chain network's expected profit under all the scenarios. Constraint (3) represents that the products can only be distributed along the feasible routes in the network in each scenario s, where W is a given big positive. Constraints (4) and (5) impose the capacity restrictions on the located facilities. Constraint (6) implies that the cost expense of locating the facilities in the network cannot exceed the budget. Constraint (7) imposes the amount of product p shipped along route $r \in R^i$ that should be less than the maximum capacity of manufacturer i. Constraint (8) means the product flow in the network is positive. Constraint (9) includes two binary variables used to decide whether a facility should be established.

Problems (2)–(9) cannot be solved efficiently due to the nonlinear term $\int_0^{\sum_{r \in R^m} X_{psr}} F(D_{mp}) dD_{mp}$ in (2). For example, if the demand follows a normal distribution, calculating this term is not straightforward since the integral of cumulative distribution function cannot be a closed form. We use a piecewise linear transformation to convert the nonlinear function into a linear one in each interval divided by golden section method. The linearized function is not exactly the same as the original nonlinear one, which will result in an error between the two. However, the error can be decreased by increasing the number of intervals. Figure 2 shows the linearization approximation process of continuous nonlinear function $f(x)$ ($x \in [x_l, x_u]$, $L = x_u - x_l$). Let $x_1 = x_l$

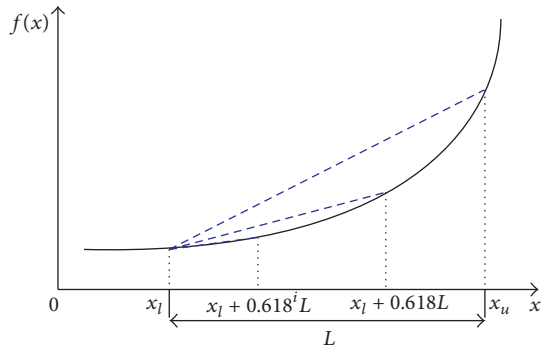

Figure 2: Piecewise linearization of a nonlinear function.

and $y_1 = f(x_1)$; we then obtain the first golden section ratio $x_2 = x_1 + 0.618 \cdot L$ corresponding to a function value y_2 and a linear equation $y = k(x-x_1)+y_1$ with slope $k = (y_2-y_1)/(x_2-x_1) = (y_2 - y_1)/(0.618 \cdot L)$ on the interval $[x_1, x_2]$. Similarly, we have the ith golden section ratio $x_2 = x_1 + 0.618^i \cdot L$ when starting from the initial point x_1 and the corresponding linear equation $y = k_i(x-x_1)+y_1$ with the slope $k_i = (y_2-y_1)/(x_2-x_1) = (y_2-y_1)/(0.618^i \cdot L)$. Consider the fitting error, denoted by $\varepsilon = y - f(x) = k_i(x-x_1)+y_1-f(x)$. The maximum error $\varepsilon_{\max}$ is achieved at $d\varepsilon/dx = k_i - f'(x) = 0$. The linear equation $y = k_i(x-x_1)+y_1$ can be used to approximately substitute the nonlinear term on the interval $[x_1, x_2]$ if the maximum error is allowable. Otherwise, we can continue to consider $(i+1)$th golden section ratio. Let x_2 be an initial point and follow the process above to perform the next linearization until we get the piecewise linear functions on the whole interval $[x_l, x_u]$.

Let $n^m \in N^m = \{1, 2, \ldots\}$ signify the set of approximation intervals for each market m, and define a_{n^m} and b_{n^m} as the slope coefficient and intercept of the linear function for interval n^m of market m, respectively. Besides, u_{n^m} and d_{n^m} are specified to represent the lower and upper bounds for interval n^m of market m. The decision variable Q_{psr} can thus be replaced with $Q_{n^m psr}$ which expresses the amount of product p shipped along route r in scenario s for the interval n^m. Therefore, the SCD design model (2)–(9) can be reformulated as the following linear program:

$$\max \quad \sum_{s\in S} p_s \cdot \pi_s - \sum_{j\in J} G_j \cdot \kappa_j - \sum_{m\in M} L_m \cdot \zeta_m \tag{10}$$

$$\text{s.t.} \quad \pi_s = \sum_{m\in M}\sum_{p\in P}\left(P_{mp}+C_{mp}\right)\cdot \sum_{r\in R^m}\sum_{n^m\in N^m} Q_{n^m psr} - \sum_{m\in M}\sum_{p\in P}\left(P_{mp}+C_{mp}-V_{mp}\right)\sum_{n^m\in N^m}\left(a_{n^m}\sum_{r\in R^m} Q_{n^m psr} + b_{n^m}\theta_{n^m ps}\right) - \sum_{m\in M}\sum_{p\in P} C_{mp}\cdot E\left[D_{mp}\right]\cdot\zeta_m - \sum_{p\in P}\sum_{r\in R^m} H_{pr}\cdot\sum_{n^m\in N^m} Q_{n^m psr}, \quad \forall s\in S, \tag{11}$$

$$\sum_{m\in M}\sum_{n^m\in N^m}\sum_{p\in P}\sum_{r\in R^j} Q_{n^m psr} \le W\cdot\kappa_j, \quad \forall j\in J,\ \forall s\in S, \tag{12}$$

$$\sum_{m\in M}\sum_{n^m\in N^m}\sum_{p\in P}\sum_{r\in R^m} Q_{n^m psr} \le W\cdot\zeta_m, \quad \forall m\in M,\ \forall s\in S, \tag{13}$$

$$\sum_{m\in M}\sum_{n^m\in N^m}\sum_{r\in R^i} Q_{n^m psr} \le U_{ip}, \quad \forall i\in I,\ \forall p\in P,\ \forall s\in S, \tag{14}$$

$$\sum_{j\in J} G_j\cdot\kappa_j + \sum_{m\in M} L_m\cdot\zeta_m \le y, \tag{15}$$

$$\sum_{n^m\in N^m}\theta_{n^m ps} = 1, \quad \forall p\in P,\ \forall s\in S, \tag{16}$$

$$\sum_{r\in R^m} Q_{n^m psr} \le u_{n^m}\cdot\theta_{n^m ps}, \quad \forall n^m\in N^m,\ \forall s\in S,\ \forall p\in P, \tag{17}$$

$$\sum_{r\in R^m} Q_{n^m psr} \ge d_{n^m}\cdot\theta_{n^m ps}, \quad \forall n^m\in N^m,\ \forall s\in S,\ \forall p\in P, \tag{18}$$

$$Q_{n^m psr} \ge 0, \quad \forall n^m\in N^m,\ \forall p\in P,\ \forall s\in S,\ \forall r\in R, \tag{19}$$

$$\theta_{n^m ps}\in\{0,1\}, \quad \forall n^m\in N^m,\ \forall p\in P,\ \forall s\in S, \tag{20}$$

$$\kappa_j, \zeta_m\in\{0,1\}, \quad \forall j\in J,\ \forall m\in M, \tag{21}$$

where π_s is an auxiliary variable introduced to simplify the model description. Note that the binary variable $\theta_{n^m ps}$ is equal to 1 if interval n^m is selected for product p in market m under scenario s and 0 otherwise. Constraint (16) ensures that only one interval can be selected for each market. Constraints (17)-(18) indicate the amount of product p of each interval is restricted by its boundary. Other constraints are explicated as shown above.

The optimal profit of the whole supply chain in the real scenario may differ from the objective function value derived from the proposed mathematical model; we introduce the solution robustness defined in Mulvey et al. [13] to reduce the deviation and make the SCN design model more robust:

$$\begin{aligned} \max \quad & \sum_{s\in S} p_s \cdot \pi_s - \lambda \sum_{s\in S} p_s \cdot \left(\pi_s - \sum_{s'\in S} p_{s'} \cdot \pi_{s'} \right)^2 \\ & - \sum_{j\in J} G_j \cdot \kappa_j - \sum_{m\in M} L_m \cdot \zeta_m \qquad (22a) \\ \text{s.t.} \quad & \text{constraints } (11)-(21), \end{aligned}$$

where λ denotes the weight used to measure the solution variance. The objective value of problem (22a) is less sensitive to change in the input data under all scenarios as the variable weight, λ, increases. However, the quadratic term, $\sum_{s\in S} p_s(\pi_s - \sum_{s'\in S} p_{s'}\pi_{s'})^2$, which evaluates the closeness of a solution to optimality for $s \in S$ usually requires a large computation time. Yu and Li [33] suggest that the quadratic term can be replaced with $\sum_{s\in S} p_s|\pi_s - \sum_{s'\in S} p_{s'}\pi_{s'}|$. By the approach proposed in Yu and Li [33], problem (22a) can be converted into the following equivalent linear formulation:

$$\begin{aligned} \max \quad & \sum_{s\in S} p_s \cdot \pi_s - \lambda \sum_{s\in S} p_s \\ & \cdot \left[\left(\sum_{s'\in S} p_{s'} \cdot \pi_{s'} - \pi_s \right) + 2\omega_s \right] - \sum_{j\in J} G_j \cdot \kappa_j \\ & - \sum_{m\in M} L_m \cdot \zeta_m \qquad (22b) \\ \text{s.t.} \quad & \sum_{s\in S} p_s \cdot \pi_s - \pi_s + \omega_s \geq 0, \quad \forall s \in S, \\ & \omega_s \geq 0, \quad \forall s \in S, \\ & \text{constraints } (11)-(21). \end{aligned}$$

Note that if $\sum_{s'\in S} p_{s'} \cdot \pi_{s'} - \pi_s \geq 0 \ \forall s \in S$, the maximization objective requires $\omega_s = 0$; otherwise, $\omega_s = \pi_s - \sum_{s\in S} p_s \cdot \pi_s$ due to the first constraint of problem (22b). Therefore, the solution of problem (22b) is similar to that of problem (22a) when the quadratic term $\sum_{s\in S} p_s(\pi_s - \sum_{s'\in S} p_{s'}\pi_{s'})^2$ is replaced by $\sum_{s\in S} p_s|\pi_s - \sum_{s'\in S} p_{s'}\pi_{s'}|$. Obviously, problem (22b) is a linear program and can thus be solved efficiently when the probability of the disruption occurrence of scenario $s \in S$ is known. However, it is difficult or impossible to estimate the actual distribution of uncertain parameters due to the lack of the historical data, especially for those rare events [20]. In the next section, we will further discuss the situation that the accurate probability of supply disruption is unavailable.

4. Robust SCN Design Model under Uncertain Supply Disruption Probability

Assume the probability distribution of the supply disruption is not complete and only known to belong to an uncertain set $\mathscr{P}$ with $\mathbf{pr} \in \mathscr{P}$, $\mathbf{pr} = (p_1, p_2, \ldots, p_{N_s})^T$. The robust counterpart of problem (22b) can be formulated as

$$\begin{aligned} \max_{\boldsymbol{\Theta},\boldsymbol{\omega}} \min_{\mathbf{pr}\in\mathscr{P}} \quad & \sum_{s\in S} p_s \cdot \pi_s - \lambda \sum_{s\in S} p_s \\ & \cdot \left[\left(\sum_{s'\in S} p_{s'} \cdot \pi_{s'} - \pi_s \right) + 2\omega_s \right] - \sum_{j\in J} G_j \\ & \cdot \kappa_j - \sum_{m\in M} L_m \cdot \zeta_m \qquad (23) \\ \text{s.t.} \quad & \min_{\mathbf{pr}\in\mathscr{P}} \sum_{s\in S} p_s \cdot \pi_s \geq \pi_s - \omega_s, \quad \forall s \in S, \\ & \omega_s \geq 0, \quad \forall s \in S, \\ & \text{constraints } (11)-(21), \end{aligned}$$

where $\boldsymbol{\Theta} \in R^{N_d}$ denotes the set of the decision variables and $\boldsymbol{\omega} = (\omega_1, \omega_2, \ldots, \omega_{N_s})^T$ is the auxiliary vector [33]. Note that problem (23) cannot be solved directly due to the min operators in both objective function and the first constraint. In the following, we introduce two uncertainty sets, namely, box and ellipsoid. Problem (23) can thus be transformed into a linear program and a second-order cone program, respectively.

4.1. Robust SCN Design Model under Box Uncertainty. The box uncertainty set to which the probability of the supply disruption scenario belongs is defined as follows:

$$\mathbf{pr} \in \mathscr{P}_I \triangleq \left\{ \mathbf{pr} \mid \mathbf{pr} = \overline{\mathbf{p}} + \boldsymbol{\xi}, \ \mathbf{e}^T\boldsymbol{\xi} = 0, \ \underline{\boldsymbol{\xi}} \leq \boldsymbol{\xi} \leq \overline{\boldsymbol{\xi}} \right\}, \qquad (24)$$

where $\overline{\mathbf{p}} = (\overline{p}_1, \overline{p}_2, \ldots, \overline{p}_{N_s})^T$ is a nominal distribution that represents the most likely distribution of the disruption probability, $\boldsymbol{\xi} \in [\underline{\boldsymbol{\xi}}, \overline{\boldsymbol{\xi}}]$ denotes the uncertain parameter vector, and $\mathbf{e}$ signifies the vector of one. The constraint $\mathbf{e}^T\boldsymbol{\xi} = 0$ ensures $\mathbf{pr}$ will meet the requirement of the probability distribution.

Let us first consider the following max-min optimization problem in (24):

$$\max_{\boldsymbol{\Theta},\boldsymbol{\omega}} \min_{\mathbf{pr}\in\mathscr{P}_I} \quad (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \mathbf{pr} - \overline{f}, \qquad (25)$$

where $\boldsymbol{\pi} = (\pi_1, \pi_2, \ldots, \pi_{N_s})^T$ and $\overline{f} = \sum_{j\in J} G_j \cdot \kappa_j + \sum_{m\in M} L_m \cdot \zeta_m$. The inner minimization problem is

$$\begin{aligned} \min_{\mathbf{pr}\in\mathscr{P}_I} \quad & \left\{ (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \mathbf{pr} - \overline{f} \right\} \\ & = (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \overline{\mathbf{p}} + \mathscr{G}^* (\boldsymbol{\xi}) - \overline{f}, \end{aligned} \qquad (26)$$

where $\mathscr{G}^*(\boldsymbol{\xi})$ is the optimal value of the following problem:

$$\min_{\boldsymbol{\xi}} \quad \left\{(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \boldsymbol{\xi} \mid \mathbf{e}^T\boldsymbol{\xi} = 0,\ \underline{\boldsymbol{\xi}} \le \boldsymbol{\xi} \le \overline{\boldsymbol{\xi}}\right\}. \tag{27}$$

The dual program of (27) can be described as follows:

$$\max_{\delta,\boldsymbol{\tau},\boldsymbol{\nu}} \quad \left\{\overline{\boldsymbol{\xi}}^T\boldsymbol{\tau} + \underline{\boldsymbol{\xi}}^T\boldsymbol{\nu} \mid \mathbf{e}\delta + \boldsymbol{\tau} + \boldsymbol{\nu} = \boldsymbol{\pi} - 2\lambda\boldsymbol{\omega},\ \boldsymbol{\tau} \le \mathbf{0},\ \boldsymbol{\nu} \ge \mathbf{0}\right\}. \tag{28}$$

According to the linear programming duality theory, it can be seen that the optimal value of the objective function in problem (27) is equal to that in (28). Following the similar mathematic process, the left-hand side of the first constraint in (23) is given by

$$\begin{aligned}\min_{\mathbf{pr}\in\mathscr{P}_I} \quad & \boldsymbol{\pi}^T\mathbf{pr} \\ &= \min_{\boldsymbol{\xi}} \left\{\boldsymbol{\pi}^T\overline{\mathbf{p}} + \boldsymbol{\pi}^T\boldsymbol{\xi} \mid \mathbf{e}^T\boldsymbol{\xi} = 0,\ \underline{\boldsymbol{\xi}} \le \boldsymbol{\xi} \le \overline{\boldsymbol{\xi}}\right\} \\ &= \boldsymbol{\pi}^T\overline{\mathbf{p}} + \mathscr{R}^*(\boldsymbol{\xi}),\end{aligned} \tag{29}$$

where $\mathscr{R}^*(\boldsymbol{\xi})$ is the optimal value of $\min_{\boldsymbol{\xi}}\{\boldsymbol{\pi}\boldsymbol{\xi} \mid \mathbf{e}^T\boldsymbol{\xi} = 0,\ \underline{\boldsymbol{\xi}} \le \boldsymbol{\xi} \le \overline{\boldsymbol{\xi}}\}$, which has the following dual problem:

$$\max_{\gamma,\boldsymbol{\alpha},\boldsymbol{\beta}} \quad \left\{\overline{\boldsymbol{\xi}}^T\boldsymbol{\alpha} + \underline{\boldsymbol{\xi}}^T\boldsymbol{\beta} \mid \mathbf{e}\gamma + \boldsymbol{\alpha} + \boldsymbol{\beta} = \boldsymbol{\pi},\ \boldsymbol{\alpha} \le \mathbf{0},\ \boldsymbol{\beta} \le \mathbf{0}\right\}. \tag{30}$$

Now, consider the following optimization problem:

$$\begin{aligned}\max_{\substack{\boldsymbol{\Theta},\boldsymbol{\omega},\delta,\boldsymbol{\tau}\\ \boldsymbol{\nu},\gamma,\boldsymbol{\alpha},\boldsymbol{\beta}}} \quad & (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\overline{\mathbf{p}} + \overline{\boldsymbol{\xi}}^T\boldsymbol{\tau} + \underline{\boldsymbol{\xi}}^T\boldsymbol{\nu} - \overline{f} \\ \text{s.t.} \quad & \mathbf{e}\delta + \boldsymbol{\tau} + \boldsymbol{\nu} = \boldsymbol{\pi} - 2\lambda\boldsymbol{\omega}, \\ & \mathbf{e}\gamma + \boldsymbol{\alpha} + \boldsymbol{\beta} = \boldsymbol{\pi}, \\ & \boldsymbol{\pi}^T\overline{\mathbf{p}} + \overline{\boldsymbol{\xi}}^T\boldsymbol{\alpha} + \underline{\boldsymbol{\xi}}^T\boldsymbol{\beta} \ge \pi_s - \omega_s, \quad \forall s \in S, \\ & \boldsymbol{\tau} \le \mathbf{0},\ \boldsymbol{\nu} \ge \mathbf{0},\ \boldsymbol{\alpha} \le \mathbf{0},\ \boldsymbol{\beta} \ge \mathbf{0}, \\ & \omega_s \ge 0, \quad \forall s \in S, \\ & \text{constraints (11)–(21)}.\end{aligned} \tag{31}$$

Proposition 1 shows that solving (23) under box uncertainty is equivalent to solving (31) with variables $(\boldsymbol{\Theta}, \boldsymbol{\omega}, \delta, \boldsymbol{\tau}, \boldsymbol{\nu}, \gamma, \boldsymbol{\alpha}, \boldsymbol{\beta}) \in R^{N_d} \times R \times R^{N_s} \times R^{N_s} \times R \times R^{N_s} \times R^{N_s}$.

Proposition 1. *If the solution $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*, \delta^*, \boldsymbol{\tau}^*, \boldsymbol{\nu}^*, \gamma^*, \boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ solves (31), then the solution $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*)$ solves (23) with $\mathscr{P} = \mathscr{P}_I$, and, conversely, if the solution $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*)$ solves (23) with $\mathscr{P} = \mathscr{P}_I$, then $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*, \overline{\delta}^*, \overline{\boldsymbol{\tau}}^*, \overline{\boldsymbol{\nu}}^*, \overline{\gamma}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\boldsymbol{\beta}}^*)$ solves (31), where $(\overline{\delta}^*, \overline{\boldsymbol{\tau}}^*, \overline{\boldsymbol{\nu}}^*)$ and $(\overline{\gamma}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\boldsymbol{\beta}}^*)$ are the optimal solutions of (28) and (30), respectively.*

Proof. Let $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*, \delta^*, \boldsymbol{\tau}^*, \boldsymbol{\nu}^*, \gamma^*, \boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ be a solution to (31); then, $(\delta^*, \boldsymbol{\tau}^*, \boldsymbol{\nu}^*)$ and $(\gamma^*, \boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ would be feasible to (28) and (30), respectively. Assuming there exists another solution $(\widetilde{\boldsymbol{\Theta}}^*, \widetilde{\boldsymbol{\omega}}^*)$ to problem (23) such that $\Upsilon(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*) < \Upsilon(\widetilde{\boldsymbol{\Theta}}^*, \widetilde{\boldsymbol{\omega}}^*)$, where $\Upsilon(\boldsymbol{\Theta}, \boldsymbol{\omega}) = \min_{\mathbf{pr}\in\mathscr{P}_I}(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\mathbf{pr} - \overline{f}$, we can obtain $(\widetilde{\delta}^*, \widetilde{\boldsymbol{\tau}}^*, \widetilde{\boldsymbol{\nu}}^*)$ and $(\widetilde{\gamma}^*, \widetilde{\boldsymbol{\alpha}}^*, \widetilde{\boldsymbol{\beta}}^*)$ by solving (28) and (30), respectively. It can be seen that $(\widetilde{\boldsymbol{\Theta}}^*, \widetilde{\boldsymbol{\omega}}^*, \widetilde{\delta}^*, \widetilde{\boldsymbol{\tau}}^*, \widetilde{\boldsymbol{\nu}}^*, \widetilde{\gamma}^*, \widetilde{\boldsymbol{\alpha}}^*, \widetilde{\boldsymbol{\beta}}^*)$ is also feasible to (30). Since the objective functions of (23) and (31) have the same form, it contradicts the assumption that $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*, \delta^*, \boldsymbol{\tau}^*, \boldsymbol{\nu}^*, \gamma^*, \boldsymbol{\alpha}^*, \boldsymbol{\beta}^*)$ is a solution to (31) due to $\Upsilon(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*) < \Upsilon(\widetilde{\boldsymbol{\Theta}}^*, \widetilde{\boldsymbol{\omega}}^*)$. Therefore, $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*)$ is a solution to (23).

Conversely, if $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*)$ is optimal to (23), then $(\overline{\delta}^*, \overline{\boldsymbol{\tau}}^*, \overline{\boldsymbol{\nu}}^*)$ and $(\overline{\gamma}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\boldsymbol{\beta}}^*)$ would be solutions to (28) and (30), respectively. Obviously, $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*, \overline{\delta}^*, \overline{\boldsymbol{\tau}}^*, \overline{\boldsymbol{\nu}}^*, \overline{\gamma}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\boldsymbol{\beta}}^*)$ is also a feasible solution to problem (31). If there exists a different solution $(\widetilde{\overline{\boldsymbol{\Theta}}}^*, \widetilde{\overline{\boldsymbol{\omega}}}^*, \widetilde{\overline{\delta}}^*, \widetilde{\overline{\boldsymbol{\tau}}}^*, \widetilde{\overline{\boldsymbol{\nu}}}^*, \widetilde{\overline{\gamma}}^*, \widetilde{\overline{\boldsymbol{\alpha}}}^*, \widetilde{\overline{\boldsymbol{\beta}}}^*)$ to (31), then from the discussion of the first part of the proof, $(\widetilde{\overline{\boldsymbol{\Theta}}}^*, \widetilde{\overline{\boldsymbol{\omega}}}^*)$ is an optimal solution to (23), which contradicts the assumption that $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*)$ solves (23). Hence, $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*, \overline{\delta}^*, \overline{\boldsymbol{\tau}}^*, \overline{\boldsymbol{\nu}}^*, \overline{\gamma}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\boldsymbol{\beta}}^*)$ solves (31). □

Clearly, problem (31) is a linear program and can thus be solved efficiently. In particular, problem (31) is reduced to a stochastic optimization problem with known disruption occurrence probability when $\underline{\boldsymbol{\xi}} = \overline{\boldsymbol{\xi}} = \mathbf{0}$. Note that if $\underline{\boldsymbol{\xi}} \ge \mathbf{0}$, we can increase the value of $\overline{\mathbf{p}}$ to attain $\underline{\boldsymbol{\xi}} < \mathbf{0}$. Hence, we can always make sure that $\underline{\boldsymbol{\xi}} < \mathbf{0}$ and $\overline{\boldsymbol{\xi}} > \mathbf{0}$ hold. The constraints $\boldsymbol{\tau} \le \mathbf{0}$ and $\boldsymbol{\nu} \ge \mathbf{0}$ in (31) imply that the term, $\overline{\boldsymbol{\xi}}^T\boldsymbol{\tau} + \underline{\boldsymbol{\xi}}^T\boldsymbol{\nu}$, is a negative reflecting the performance loss caused by the uncertainty.

4.2. Robust SCN Design Model under Ellipsoid Uncertainty. The ellipsoid uncertainty set to which the probability of the supply disruption scenario belongs is defined as follows:

$$\begin{aligned}\mathbf{pr} \in \mathscr{P}_E \triangleq \Big\{\mathbf{pr} \mid\ & \mathbf{pr} = \overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi},\ \overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi} \ge \mathbf{0},\ \mathbf{e}^T\mathbf{A}\boldsymbol{\xi} \\ & = 0,\ \|\boldsymbol{\xi}\| \le 1\Big\},\end{aligned} \tag{32}$$

where $\overline{\mathbf{p}}$ is the most likely distribution which is the center of the ellipsoid. $\|\cdot\|$ is the Euclidean norm, and $\|\cdot\|_*$ is its dual representation. Due to the self-duality of Euclidean norm, we have $\|\cdot\|_* = \|\cdot\|$. $\mathbf{A} \in R^{n\times n}$ is a known scaling matrix to measure the degree of the uncertainty. The constraints $\mathbf{e}^T\mathbf{A}\boldsymbol{\xi} = 0$ and $\overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi} \ge 0$ ensure that the vector $\mathbf{pr}$ is a probability distribution. Hence, the objective of problem (23) can be formulated as follows:

$$\max_{\boldsymbol{\Theta},\boldsymbol{\omega}} \min_{\mathbf{pr}\in\mathscr{P}_E} \quad (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\mathbf{pr} - \overline{f}. \tag{33}$$

Consider the following inner optimization problem of problem (33):

$$\begin{aligned}\min_{\mathbf{pr}\in\mathscr{P}_E} \quad & \left\{(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\mathbf{pr} - \overline{f}\right\} \\ & = (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\overline{\mathbf{p}} + \mathscr{Q}^*(\boldsymbol{\xi}) - \overline{f},\end{aligned} \tag{34}$$

where $\mathcal{Q}^*(\boldsymbol{\xi})$ is the optimal value of the following problem:

$$\min_{\boldsymbol{\xi}} \quad \left\{(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \mathbf{A}\boldsymbol{\xi} \mid \overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi} \geq \mathbf{0},\ \mathbf{e}^T\mathbf{A}\boldsymbol{\xi} = \mathbf{0},\ \|\boldsymbol{\xi}\| \leq \mathbf{1}\right\}. \quad (35)$$

It can be seen that problem (35) is a second-order cone program with the variable vector $\boldsymbol{\xi}$ and its Lagrange is defined as

$$\begin{aligned}\mathscr{L}(\boldsymbol{\eta}, \rho, \mu; \boldsymbol{\xi}) &= (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T \mathbf{A}\boldsymbol{\xi} + \boldsymbol{\eta}^T(-\overline{\mathbf{p}} - \mathbf{A}\boldsymbol{\xi}) \\ &\quad + \rho(\|\boldsymbol{\xi}\| - 1) + \mu\mathbf{e}^T\mathbf{A}\boldsymbol{\xi}.\end{aligned} \quad (36)$$

The Lagrange dual function with $(\boldsymbol{\eta}, \rho, \mu) \in R^{N_S} \times R \times R$ is given by

$$\begin{aligned}g(\boldsymbol{\eta}, \rho, \mu) &= \min_{\boldsymbol{\xi}} \mathscr{L}(\boldsymbol{\eta}, \rho, \mu; \boldsymbol{\xi}) = \left(-\overline{\mathbf{p}}^T\boldsymbol{\eta} - \rho\right) \\ &\quad - \max_{\boldsymbol{\xi}} \left\{\left(-\mathbf{A}^T(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega}) + \mathbf{A}^T\boldsymbol{\eta} - \mathbf{A}^T\mathbf{e}\mu\right)^T \boldsymbol{\xi}\right. \\ &\quad \left. - \rho\|\boldsymbol{\xi}\|\right\} = \left(-\overline{\mathbf{p}}^T\boldsymbol{\eta} - \rho\right) - \Lambda^*\left(-\mathbf{A}^T(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})\right. \\ &\quad \left. + \mathbf{A}^T\boldsymbol{\eta} - \mathbf{A}^T\mathbf{e}\mu\right),\end{aligned} \quad (37)$$

where $\Lambda^*(\mathbf{y}) = \{0,\ \|\mathbf{y}\|_* \leq \rho;\ \infty,\ \|\mathbf{y}\|_* > \rho\}$ is the conjugate function of $\Lambda(\boldsymbol{\xi}) = \rho\|\boldsymbol{\xi}\|$. Then, the Lagrange dual problem associated with problem (35) is given by

$$\max_{\boldsymbol{\eta},\rho,\mu} \quad g(\boldsymbol{\eta}, \rho, \mu) = \max_{\boldsymbol{\eta},\rho,\mu} \left\{-\overline{\mathbf{p}}^T\boldsymbol{\eta} - \rho \mid \left\|-\mathbf{A}^T(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega}) + \mathbf{A}^T\boldsymbol{\eta} - \mathbf{A}^T\mathbf{e}\mu\right\| \leq \rho,\ \boldsymbol{\eta} \geq \mathbf{0},\ \rho \geq 0\right\}. \quad (38)$$

Obviously, problem (38) is a concave program. According to the characteristic of a probability distribution, there exists a disturbance vector $\boldsymbol{\xi}$ such that $\overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi} > \mathbf{0}$, which means Slater's condition holds. Therefore, in light of the strong duality theorem of Lagrange, problem (34) is equivalent to the following maximization problem with variables $(\boldsymbol{\Theta}, \boldsymbol{\omega}, \boldsymbol{\eta}, \rho, \mu) \in R^{N_d} \times R^{N_S} \times R^{N_S} \times R \times R$:

$$\begin{aligned}\max_{\boldsymbol{\Theta},\boldsymbol{\eta},\rho,\mu} \quad & (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\overline{\mathbf{p}} - \overline{\mathbf{p}}^T\boldsymbol{\eta} - \rho - \overline{f} \\ \text{s.t.} \quad & \left\|-\mathbf{A}^T(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega}) + \mathbf{A}^T\boldsymbol{\eta} - \mathbf{A}^T\mathbf{e}\mu\right\| \leq \rho, \\ & \boldsymbol{\eta} \geq \mathbf{0},\ \rho \geq 0.\end{aligned} \quad (39)$$

Following the logic above, we have the equivalent formulation of the left-hand side of the first constraint in (23) as follows:

$$\begin{aligned}\min_{\mathbf{pr}\in\mathscr{P}_E} \quad \boldsymbol{\pi}^T\mathbf{pr} &= \min_{\boldsymbol{\xi}} \left\{\boldsymbol{\pi}^T\overline{\mathbf{p}} + \boldsymbol{\pi}^T\mathbf{A}\boldsymbol{\xi} \mid \overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi}\right. \\ &\quad \left. \geq \mathbf{0},\ \mathbf{e}^T\mathbf{A}\boldsymbol{\xi} = 0,\ \|\boldsymbol{\xi}\| \leq 1\right\} = \boldsymbol{\pi}^T\overline{\mathbf{p}} + \mathscr{H}^*(\boldsymbol{\xi}),\end{aligned} \quad (40)$$

where $\mathscr{H}^*(\boldsymbol{\xi})$ is the optimal value of $\min_{\boldsymbol{\xi}}\{\boldsymbol{\pi}^T\mathbf{A}\boldsymbol{\xi} \mid \overline{\mathbf{p}} + \mathbf{A}\boldsymbol{\xi} \geq \mathbf{0},\ \mathbf{e}^T\mathbf{A}\boldsymbol{\xi} = 0,\ \|\boldsymbol{\xi}\| \leq 1\}$ which is equivalent to the following dual program:

$$\max_{\boldsymbol{\alpha},\gamma,\beta} \quad \left\{-\overline{\mathbf{p}}^T\boldsymbol{\alpha} - \beta \mid \left\|-\mathbf{A}^T\boldsymbol{\pi} + \mathbf{A}^T\boldsymbol{\alpha} - \mathbf{A}^T\mathbf{e}\gamma\right\| \leq \beta,\ \boldsymbol{\alpha} \geq \mathbf{0},\ \beta \geq 0\right\}. \quad (41)$$

Consider the following optimal problem with variables $(\boldsymbol{\Theta}, \boldsymbol{\omega}, \boldsymbol{\eta}, \rho, \mu, \boldsymbol{\alpha}, \beta, \gamma) \in R^{N_d} \times R^{N_S} \times R^{N_S} \times R \times R \times R^{N_S} \times R \times R$:

$$\begin{aligned}\max_{\substack{\boldsymbol{\Theta},\boldsymbol{\omega},\boldsymbol{\eta},\rho \\ \mu,\boldsymbol{\alpha},\beta,\gamma}} \quad & (\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega})^T\overline{\mathbf{p}} - \overline{\mathbf{p}}^T\boldsymbol{\eta} - \rho - \overline{f} \\ \text{s.t.} \quad & \left\|-\mathbf{A}^T(\boldsymbol{\pi} - 2\lambda\boldsymbol{\omega}) + \mathbf{A}^T\boldsymbol{\eta} - \mathbf{A}^T\mathbf{e}\mu\right\| \leq \rho, \\ & \left\|-\mathbf{A}^T\boldsymbol{\pi} + \mathbf{A}^T\boldsymbol{\alpha} - \mathbf{A}^T\mathbf{e}\gamma\right\| \leq \beta, \\ & \boldsymbol{\pi}^T\overline{\mathbf{p}} - \overline{\mathbf{p}}^T\boldsymbol{\alpha} - \beta \geq \pi_s - \omega_s, \quad \forall s \in S, \\ & \boldsymbol{\eta} \geq \mathbf{0},\ \boldsymbol{\alpha} \geq \mathbf{0},\ \rho \geq 0,\ \beta \geq 0, \\ & \omega_s \geq 0,\ \forall s \in S, \\ & \text{Constraints } (11) - (21).\end{aligned} \quad (42)$$

Proposition 2 shows that solving (23) under ellipsoid uncertainty is equivalent to solving (42).

Proposition 2. *If the solution* $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*, \boldsymbol{\eta}^*, \rho^*, \mu^*, \boldsymbol{\alpha}^*, \beta^*, \gamma^*)$ *solves (42), then* $(\boldsymbol{\Theta}^*, \boldsymbol{\omega}^*)$ *solves (23) with* $\mathscr{P} = \mathscr{P}_E$*, and, conversely, if the solution* $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*)$ *solves optimization problem (23) with* $\mathscr{P} = \mathscr{P}_E$*, then* $(\overline{\boldsymbol{\Theta}}^*, \overline{\boldsymbol{\omega}}^*, \overline{\boldsymbol{\eta}}^*, \overline{\rho}^*, \overline{\mu}^*, \overline{\boldsymbol{\alpha}}^*, \overline{\beta}^*, \overline{\gamma}^*)$ *solves optimization problem (42), where* $(\overline{\boldsymbol{\eta}}^*, \overline{\rho}^*, \overline{\mu}^*)$ *and* $(\overline{\boldsymbol{\alpha}}^*, \overline{\beta}^*, \overline{\gamma}^*)$ *are the optimal solutions of (39) and (41), respectively.*

The proof of Proposition 2 is omitted because it is similar to that of Proposition 1. Obviously, problem (42) is a second-order cone program and can thus be solved efficiently. In particular, (42) is reduced to a stochastic optimization problem with known disruption occurrence probability when $\underline{\boldsymbol{\xi}} = \overline{\boldsymbol{\xi}} = \mathbf{0}$. Similarly, it can be observed that the uncertainty of the

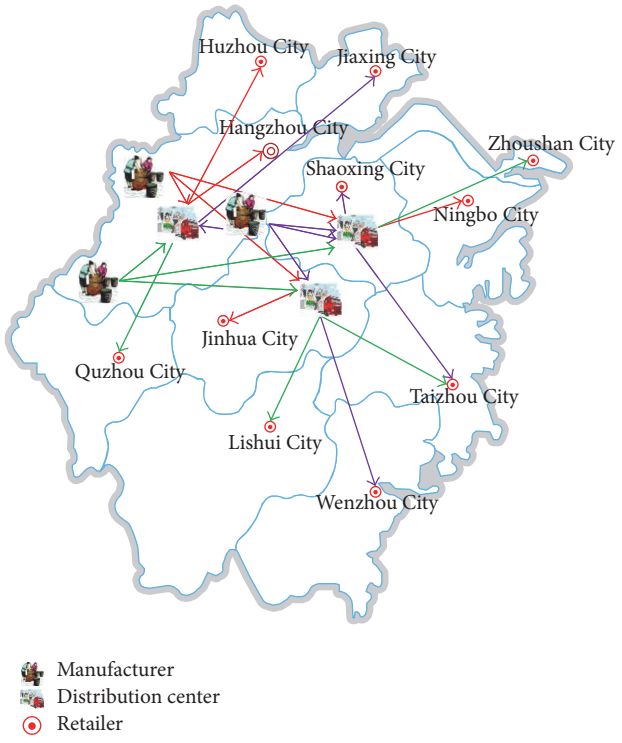

Figure 3: The potential supply chain network structure of CF Company.

disruption occurrence probability will lead to a performance loss (positive), that is, $\overline{\mathbf{p}}^T \boldsymbol{\eta} + \rho$.

Table 1: The unit handling cost on potential routes.

Potential route	Unit handling cost (H_{pr})	Potential route	Unit handling cost (H_{pr})
r_{1-1-1}	815.1	r_{2-2-9}	815.4
r_{1-1-5}	815.3	r_{2-3-3}	815.5
r_{1-2-2}	815.2	r_{3-1-8}	815.9
r_{1-3-7}	815.3	r_{3-2-11}	815.8
r_{2-1-6}	815.3	r_{3-3-9}	815.6
r_{2-2-4}	815.2	r_{3-3-10}	815.2

r_{i-j-m} dentoes a route starting from manufacturer i to retailer m by passing through distribution center j.

Table 2: The distribution of the demand for each market.

Market	Distribution
(1) Hangzhou	$D_1 \sim N(E(D_1) = 700,\ \sigma(D_1) = 5)$
(2) Ningbo	$D_2 \sim N(E(D_2) = 700,\ \sigma(D_2) = 5)$
(3) Wenzhou	$D_3 \sim N(E(D_3) = 600,\ \sigma(D_3) = 5)$
(4) Shaoxing	$D_4 \sim N(E(D_4) = 500,\ \sigma(D_4) = 5)$
(5) Huzhou	$D_5 \sim N(E(D_5) = 300,\ \sigma(D_5) = 5)$
(6) Jiaxing	$D_6 \sim N(E(D_6) = 300,\ \sigma(D_6) = 5)$
(7) Jinhua	$D_7 \sim N(E(D_7) = 600,\ \sigma(D_7) = 5)$
(8) Quzhou	$D_8 \sim N(E(D_8) = 200,\ \sigma(D_8) = 4)$
(9) Taizhou	$D_9 \sim N(E(D_9) = 500,\ \sigma(D_9) = 5)$
(10) Lishui	$D_{10} \sim N(E(D_{10}) = 200,\ \sigma(D_{10}) = 4)$
(11) Zhoushan	$D_{11} \sim N(E(D_{11}) = 220,\ \sigma(D_{11}) = 5)$

5. Case Study and Numerical Results

To verify the effectiveness of the proposed robust SCN design models and solution approaches, we consider a three-tiered supply chain network design for a real-life company in Hangzhou City of China, named CF Company, which manufactures and sales superior packed Longjing tea. The Longjing tea, produced in the surrounding mountains of the Longjing village, has efficacies of refreshing, producing saliva and slaking thirst, reducing blood lipids, lowering cholesterol, and so on. Longjing tea is usually picked and processed from March to May every year and priced from a few hundred to thousands of yuans due to the different picking time and processing technology. Due to the intense competition in local market, CF Company has to reduce the price and improve the service quality to meet the target customer group, which, however, leads to a high operation cost in return. To deal with the dilemma that the company faces, it is necessary to design an efficient and reliable supply chain network. In Figure 3, we illustrate the potential supply chain network structure of CF Company who has three available plants in Hangzhou, three potential distribution centers located at candidate locations of Hangzhou, Shaoxing, and Jiaxing, respectively, and eleven potential retailers located successively in Hangzhou, Ningbo, Wenzhou, Shaoxing, Huzhou, Jiaxing, Jinhua, Quzhou, Taizhou, Lishui, and Zhoushan.

There are twelve feasible routes in the potential supply chain network with handling costs given in Table 1. After a series of processes such as picking, spreading, fixing, shaping, and drying, the production of Longjing tea is completed and then packed into finished products (500 g per box). The unit prices of the product for all markets are 965, 965, 966, 965, 965, 965, 965, 966, 965, 966, and 966, respectively. The unit shortage cost for unmet demand is 101 and the unit salvage value for residual product is 386. The maximum production capacity of each manufacture is considered as 2500, 2200, and 1200, respectively. The fixed costs for locating distribution centers at candidate locations of Hangzhou, Shaoxing, and Jiaxing are 23120, 19884, and 18888, respectively. The fixed costs of locating retailers for the abovementioned 11 markets are 5780, 5676, 5517, 4971, 4957, 4998, 4722, 4825, 5221, 4830, and 4943. The budget for establishing the facilities is 120000. The random demand of each market is assumed to follow Gaussian distribution (see Table 2). Due to confidentiality, all the data used in this paper are processed but resemble the data structure of CF Company.

We consider four possible disruption scenarios due to the manufacturers' facilities impairments and connection links interruptions. In the first scenario, all twelve potential routes are available which means there is no disruption occurring in the supply chain. The second and the third scenarios are described as only the second and the third facility break down, respectively. And in the fourth scenario, the second and the third facility fail simultaneously. The probability of each scenario to occur is only known to belong

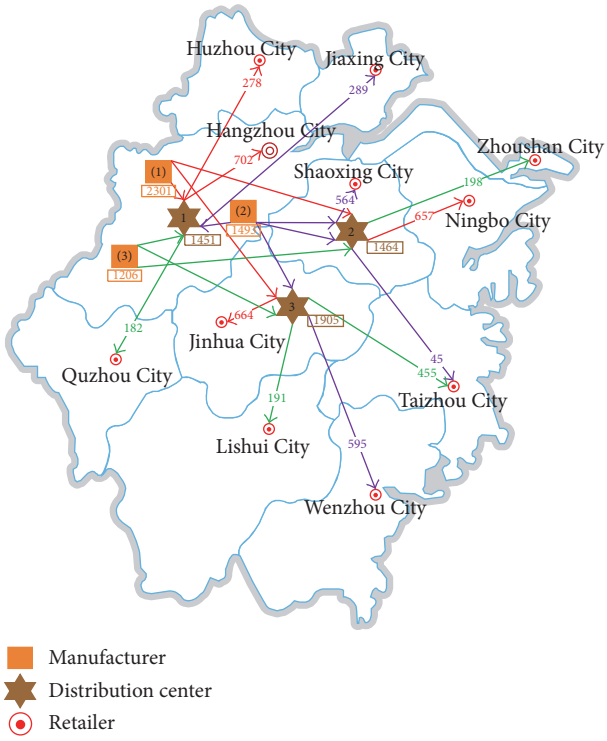

Figure 4: Network structure and operation strategies under $\overline{\mathbf{p}}$ in the first scenario.

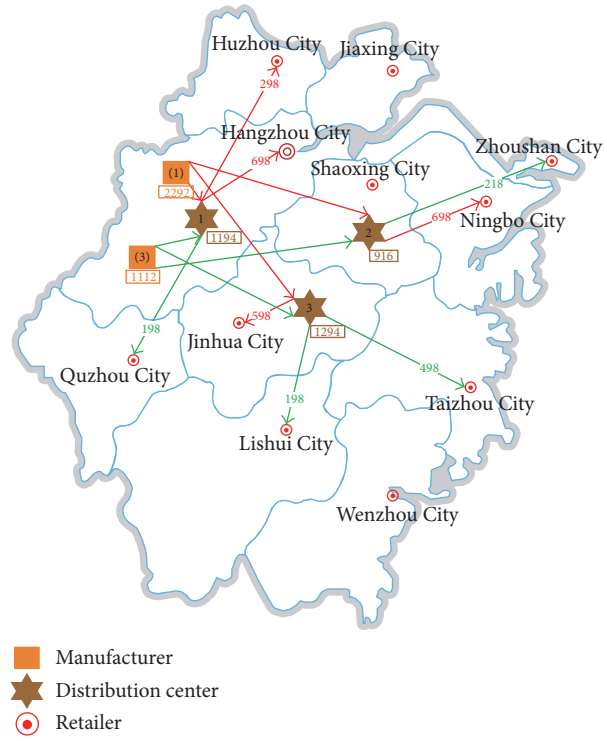

Figure 5: Network structure and operation strategies under $\overline{\mathbf{p}}$ in the second scenario.

to a specific uncertainty set, where the most likely distribution is estimated to be $\overline{\mathbf{p}} = (0.6875, 0.0500, 0.2500, 0.0125)^T$.

We break the range of each target market into ten intervals and assume $\overline{\mathbf{p}}$ is the real disruption occurrence probability distribution for the purpose of comparing the robust solution with the optimal one. Models (31) and (42) are solved with LINGO 11.00 software and the runs are performed on an Intel Core with 2 Duo CPU at 2.2 GHz. The solutions are obtained within two minutes approximately.

5.1. Results under $\overline{\mathbf{p}}$. By solving (22b) with $\mathbf{pr} = \overline{\mathbf{p}}$ and $\lambda = 2$, we obtain the optimal objective function value of 375647.3, and the corresponding optimal network structures under different scenarios are displayed in Figures 4–7, where the numbers in the boxes and lines represent the manufacturers' production quantity, distribution centers' transfer amount, and markets sales volume. From Figure 4, we find that the yields of three manufactures in the first scenario are 2301, 1493, and 1206, respectively. All the potential markets are selected and the total quantities shipped to these markets are 5000. Figure 5 (Figure 6) shows that the total yield, that is, 3404 (4184), does not reach the maximum capacity in the second (third) scenario. Compared with the first scenario, we find the production quantity in the second or third scenario is less than that in the first one due to the impairments of the manufacturers' facilities, which results in the unmet markets such as 3, 4, and 6 under the second scenario and markets 8, 10, and 11 under the third scenario. Considering that only the first facility can be usable, we find that only a few markets are selected in the fourth scenario, with the total sales volume of 2292 (see Figure 7).

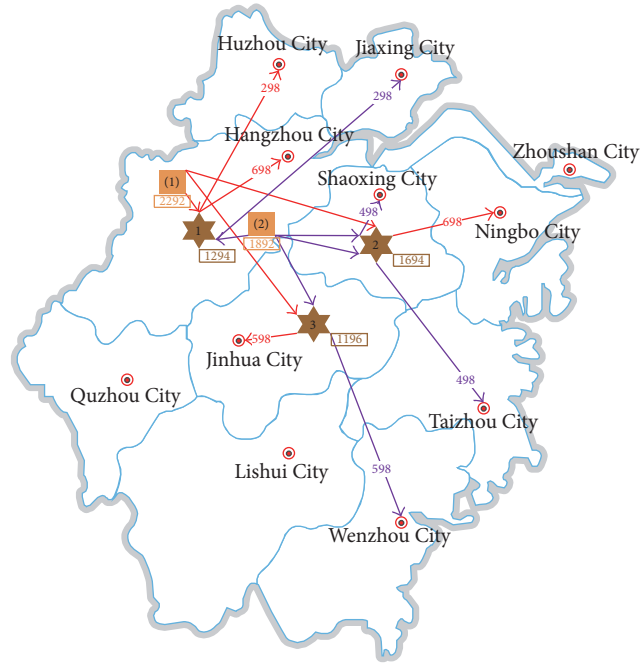

Figure 6: Network structure and operation strategies under $\overline{\mathbf{p}}$ in the third scenario.

Figure 7: Network structure and operation strategies under $\overline{\mathbf{p}}$ in the fourth scenario.

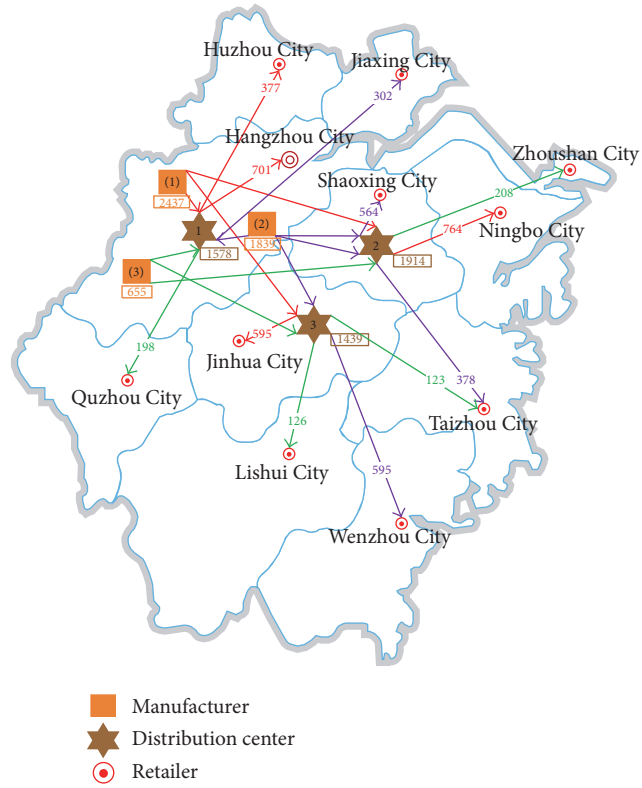

Figure 8: Network structure and operation strategies under box certainty in the first scenario.

5.2. Results under Box Uncertainty. In order to test the proposed SCN design model and the solution approach under box uncertainty, let $\boldsymbol{\xi} = g \cdot \mathbf{K}$, $\mathbf{K} \in [\underline{\mathbf{K}}, \overline{\mathbf{K}}]$, $\underline{\mathbf{K}} = (-1, -0.2, -0.6, -0.05)^T$, $\overline{\mathbf{K}} = (1, 0.2, 0.6, 0.05)^T$, $g = 0.02$, and $\lambda = 2$. By solving problem (31), we obtain the objective function value of 310826.5. However, when the solutions derived from (31) are applied to the real distribution $\overline{\mathbf{p}}$, the corresponding performance turns into 324167.4. Comparing with the optimal value of 375647.3, it can be found that the uncertainty in disruption scenario occurrence probability will inevitably lead to the performance loss ((375647.3 − 324167.4)/375647.3 = 13.7%). Furthermore, the loss can be regarded as the maximum cost for decision-makers who are willing to pay to obtain the complete disruption information. Interestingly, by observing the network structures under box uncertainty, we find that only the SCN design plan in the first scenario is different from that in the real distribution $\overline{\mathbf{p}}$ (see Figure 8). We can thus conclude that the proposed robust SCN design model and solution approach perform well under uncertainty. In particular, the network structure and corresponding operation strategies are consistent with the optimal case when the supply disruption does occur in the supply chain.

To further investigate the effectiveness of the proposed robust optimization approach, some of the probability distributions are generated according to (24) with $\overline{\mathbf{p}} = (0.6875, 0.0500, 0.2500, 0.0125)^T$, and all of them are considered as the real distributions. The calculation results are displayed in Table 3 where the numbers in the third column are obtained by applying the robust solutions to each of the real distributions generated. From Table 3, we find that the performance loss ratios change around 13.70% with relatively small amplitude, which indicates the proposed solution approach in this paper is robust to deal with uncertainty in disruption scenario probability distribution.

Since the variability weight λ places an important role in measuring the deviation between the robust performance for any scenario realization and the optimal one, more experiments are executed to observe the changing tendencies of the objective performances under different λ and the degree of uncertainty expressed with a parameter g as well. We obtain the results shown in Figure 9. From Figure 9, we find that, for a given λ or g, the performance is decreasing with the degree of the uncertainty or the variability weight λ. However, the lower the degree of the uncertainty, the smaller the decreasing amplitude, which implies the supply chain manager should gather more information to improve the forecasting precision of disruption scenario probability.

5.3. Results under Ellipsoid Uncertainty. When the probabilities that supply disruption scenarios occur belong to the ellipsoid uncertainty set defined in (32), we do the similar numerical simulations as in Section 5.2. Let $\mathbf{A} = h \cdot \mathbf{E}$, where $\mathbf{E}$ is an identity matrix, $h = 0.02$, and $\lambda = 2$. By solving (42), we obtain the objective function value of 331352.9. The solutions derived from (42) produce a performance of 341832.6 when applying them to the real distribution $\overline{\mathbf{p}}$, which leads to the performance loss ratio as

Table 3: Comparisons under different probability distributions under box uncertainty.

Scenario probability distribution	Optimal objective function value	Objective function value when applying robust solutions to a real distribution	Performance loss ratio
(0.7295, 0.0500, 0.2100, 0.0105)	379422.0	319096.0	15.90%
(0.7085, 0.0500, 0.2300, 0.0115)	377534.6	321631.7	14.81%
(0.6875, 0.0500, 0.2500, 0.0125)	375647.3	324167.4	13.70%
(0.6665, 0.0500, 0.2700, 0.0135)	373759.9	326703.0	12.59%
(0.6455, 0.0500, 0.2900, 0.0145)	371872.6	329238.7	11.46%

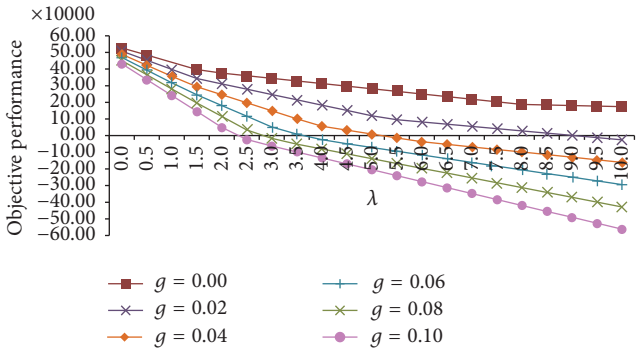

Figure 9: Sensitivity analysis on λ and g under box uncertainty.

9.00% ((375647.3 − 341832.6)/375647.3). Similarly, we also find that only the network structure and the corresponding operation strategies in the first scenario (see Figure 10) are different from the optimal case.

Similarly, in order to further examine the effectiveness of the proposed robust optimization approach under ellipsoid uncertainty, some more probability distributions are generated according to (32) with $\bar{\mathbf{p}} = (0.6875, 0.0500, 0.2500, 0.0125)^T$ and regarded as the real distributions. Following the same calculation as above, we obtain the results displayed in Table 4. From Table 4, we find that the performance loss ratios change closely around 9.00%, which validates the effectiveness of the proposed solution approach in dealing with the distributional uncertainty. Moreover, the performance changing tendencies under different variability weight λ and the degree of the uncertainty h are investigated and the results are shown in Figure 11 which reveals the similar relationships as those found in Figure 9.

6. Conclusions

In this paper, we develop a robust optimization model for designing a supply chain network including manufactures, distribution centers, and retailers under both demand uncertainty and supply disruption. For uncertain market demand, it is assumed to be random and follow a known distribution, and a piecewise linearization method is used to transform the nonlinear model caused by stochastic demand into a linear one. For supply disruption, it is described by a series

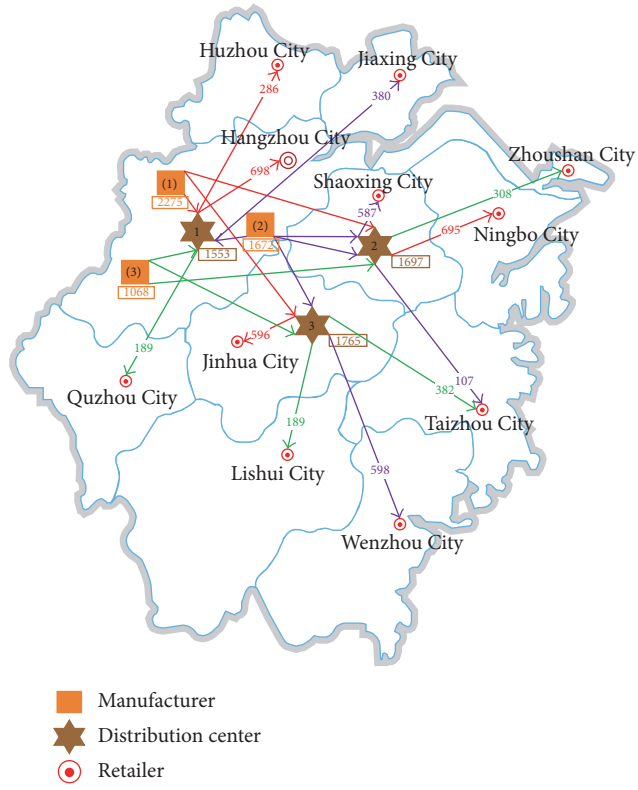

Figure 10: Network structure and operation strategies under ellipsoid uncertainty in the first scenario.

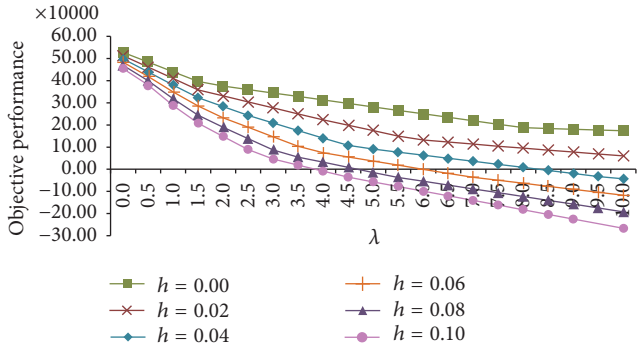

Figure 11: Sensitivity analysis on λ and h under ellipsoid uncertainty.

Table 4: Comparisons under different probability distributions under ellipsoid uncertainty.

Scenario probability distribution	Optimal objective function value	Objective function value when applying robust solutions to a real distribution	Performance loss ratio
(0.7295, 0.0500, 0.2100, 0.0105)	379422.0	337840.5	10.96%
(0.7085, 0.0500, 0.2300, 0.0115)	377534.6	339836.5	9.99%
(0.6875, 0.0500, 0.2500, 0.0125)	375647.3	341832.7	9.00%
(0.6665, 0.0500, 0.2700, 0.0135)	373759.9	343828.7	8.01%
(0.6455, 0.0500, 0.2900, 0.0145)	371872.6	345824.8	7.00%

of scenarios with unknown probabilities and the corresponding robust counterparts are presented under both box and ellipsoid uncertainty. Through mathematical propositions, we transform the robust SCN design models into tractable linear program under box uncertainty and into second-order cone program under ellipsoid uncertainty.

The proposed model and solution approach are evaluated in a real case to examine their effectiveness. The results show that the SCN designed by our approach perform well under the uncertainty in supply disruption scenario probability. In particular, the lower the degree of the uncertainty, the better the operation performance of the supply chain network. Our robust supply chain design model can be extended to multiperiod case by incorporating an inventory management policy. In addition, another interesting direction for future research is to consider other risk measurements such as conditional value at risk (CVaR) and mean CVaR to measure the performance under uncertainty which would enrich our model.

Notations

Sets

I: Set of manufacturers, indexed by i, $i \in I = \{1, 2, \ldots, N_I\}$
J: Set of potential distribution centers, indexed by j, $m \in M = \{1, 2, \ldots, N_M\}$
M: Set of markets or retailers, indexed by m, $m \in M = \{1, 2, \ldots, N_M\}$
P: Set of products, indexed by p, $p \in P = \{1, 2, \ldots, N_P\}$
S: Set of disruption scenarios, indexed by s, $s \in S = \{1, 2, \ldots, N_S\}$
R: Set of routes starting from manufacturers, passing through distribution centers, and ending at retailers, indexed by r, $r \in R = \{1, 2, \ldots, N_R\}$
R^i: Set of routes starting from manufacturer i
R^j: Set of routes passing through distribution center j
R^m: Set of routes shipped to market m.

Parameters

G_j: Fixed cost of establishing distribution center j
L_m: Fixed cost of developing market m
D_{mp}: Demand of product p in market m, which is a random variable with the mean $E[D_{mp}]$ and the cumulative distribution function $F(D_{mp})$
U_{ip}: Capacity of manufacturer i for product p
y: Cost budget for establishing facilities in supply chain network
P_{mp}: Unit sales price of product p in market m
V_{mp}: Unit salvage value of unsold product p in market m
C_{mp}: Unit shortage cost of the unmet demand for product p in market m
H_{pr}: Unit handling cost for product p along route r, including unit production cost, unit shipping cost, and unit storage cost
p_s: Probability of disruption occurrence of scenario s.

Decision Variables

Q_{psr}: Amount of product p shipped along the route r in scenario s
κ_j: Binary variable equal to 1 if a distribution center is established in location j and 0 otherwise
ζ_m: Binary variable equal to 1 if market m is opened and 0 otherwise
B_{sr}: Binary variable equal to 1 if route is available in scenario s and 0 otherwise.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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Research Article

Research on the Competitive Strategy of Cross-Border E-Commerce Comprehensive Pilot Area Based on the Spatial Competition

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By now, 13 cross-border e-commerce comprehensive pilot areas have been approved by the State Council of China; Dalian and Tianjin are two of them. But with the development of the construction of the cross-border e-commerce comprehensive pilot areas, the competition between those pilot areas is inevitable. Dalian and Tianjin are located in the Bohai Sea and the distance between them is only 800 kilometers. For Dalian and Tianjin they are in thus competitive situations: first they have to compete with each other; second since they are located in Bohai Sea (North China), they have to compete with other cross-border e-commerce comprehensive pilot areas (South China). In this paper, our aim is to build models to provide best price strategies for these two cities. Based on the two-sided market theory and the geographical position, this paper builds two competitive theory models. Through the analyzing of the equilibrium, we get two main results: (1) according to different service area, the cities (Dalian and Tianjin) should have different price; (2) the two-sided market characters have an impact on their strategies.

1. Introduction

In March 2015, the State Council established the first comprehensive pilot area of cross-border e-commerce in Hangzhou. Within one year, the transaction scale of cross-border e-commerce in Hangzhou increased from 20 million dollars in 2014 to 3.464 billion dollars in 2015, including exports accounting for 2.273 billion dollars and imports accounting for 1.191 billion dollars, which contributed 5.4% for the growth of foreign trade exports in Hangzhou. The establishment of the comprehensive pilot area of cross-border e-commerce in Hangzhou has yielded prominent results. In January 2016, the State Council decided to set up a group of new comprehensive pilot areas of cross-border e-commerce in 12 cities such as Tianjin and Shanghai, and the intention of this decision was to take example by the efficient pattern of comprehensive pilot area in Hangzhou to provide the development of Chinese foreign trade with new motivations and supports [1, 2]. But with the development of the construction of the cross-border e-commerce comprehensive pilot area, the competition between those pilot areas is inevitable. And this kind of competition has obvious spatial characteristics and two-sided market characteristics.

This article takes Tianjin and Dalian as an example to illustrate the competition among the cross-border e-commerce comprehensive pilot areas. Both Tianjin and Dalian are the second batch of the establishment of cross-border e-commerce comprehensive pilot areas in the beginning of 2016. Both of them are located in the north of China. Tianjin is in the west and Dalian is in the east. This kind of layout just divides the domestic enterprises and consumers into four parts, as shown in Figure 1.

The following analysis can be done through the angle of the geographical position: first, because Tianjin is located in the west, Dalian is located in the east. So firms and consumers in the west of Tianjin will take Tianjin as the first choice to do cross-border e-commerce; the firms and consumers in the east of Dalian will take Dalian as the first choice to do

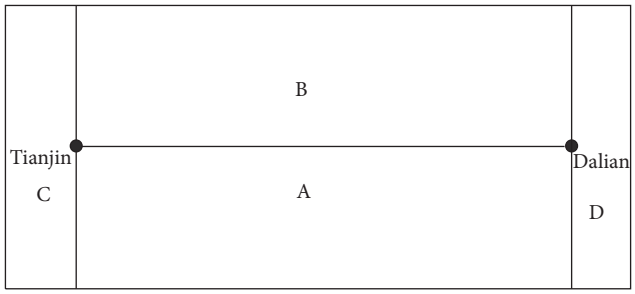

Figure 1: Location map of domestic firms and consumers.

cross-border e-commerce. At the same time the firms and consumers in the south of Dalian Tianjin line can choose Tianjin and Dalian or can also choose other comprehensive pilot areas, for example, Qingdao and Zhengzhou. Therefore, A district is under the competition of multiareas. The firms and consumers in the north of Dalian Tianjin line can only choose Dalian or Tianjin. Therefore, B district is under the competition of Dalian and Tianjin. In summary, there is no competition in C and D zones, and A and B zones are the competition zones. Therefore, this paper will analyze the competitive strategy of cross-border e-commerce comprehensive pilot areas based on spatial competition theory.

Besides, the cross-border e-commerce comprehensive pilot areas are service platforms; on the one hand, they are connecting the domestic firms and consumers, and on the other hand, they are connecting the foreign firms and consumers, so the market is typically a two-sided market [3, 4].

Until now there is no general agreement on a standard definition of two-sided market, but the definitions of Armstrong (2006) [5], Rysman (2009) [6], and Rochet and Tirole (2010) [7] are widely cited and recognized. Coase theorem and the nonneutrality of price structure are two significant features of the two-sided markets. Rochet and Tirole (2010) [7], Armstrong (2006) [5], Kaiser and Wright (2006) [8], and other scholars have proposed their own classification of two-sided market, but the classification of Evans (2003) is widely accepted. He divided the two-sided market into three classifications: market-makers, audience-makers, and demand-coordinators [9]. Cross-border e-commerce comprehensive pilot areas are platforms to do cross-border e-commerce, so they have the main characteristics of two-sided market. In this paper we use two-sided market theory to build the theory model.

Through the above analysis, we know that the firms and consumers in C zone will take Tianjin as the first choice to do cross-border e-commerce; the firms and consumers in D zone will take Dalian as the first choice to do cross-border e-commerce. So there is no need to analyze their strategies on zones C and D. Then, in this paper, we will build two competitive theory models to analyze Dalian and Tianjin's competitive strategies on zone A and zone B, respectively. Also, we will analyze how the two-sided market characteristics affect the revenue of those two cities. Although the model takes Tianjin and Dalian as an example, the conclusions are general.

The paper is organized as follows: the first part is Introduction, the second part is The Basic Model Assumptions, the third part is Model (I): Competitive Model on A Zone, the fourth part is Model (II): Competitive Model on B Zone, the fifth part makes A Comparative Analysis of Model (I) and Model (II), the sixth part shows some numerical examples, and the seventh part makes the conclusion.

2. The Basic Model Assumptions

For the convenience of analysis, in this paper, the fundamental assumptions are as follows. Firstly, we assume that there are two kinds of pilot areas: the first one is called the North area, which includes Tianjin and Dalian; the other one is called the South area, which includes other eleven cities. In the North area there are two cities: Tianjin is referred to as position i, and Dalian is referred to as position j. Secondly, hypotheses about the two-sided markets are as follows: the domestic firms and consumers (DF&Cs for short) are called side 1 and the foreign firms and consumers (FF&Cs for short) are called side 2. According to the actual situation, the DF&Cs side is single-homing and the FF&Cs side is multihoming. We assume that t_1 is the matching cost (which includes the transportation cost and other costs) of side 1 and t_2 is the matching cost of side 2, and matching cost of side 1 is equal to that of side 2; namely, $t_1 = t_2 = t$. Thirdly, the hypotheses of network effects are as follows: we assume that there are network effects between groups. The strength of network effects for DF&Cs side gathering in the position i to FF&Cs side is α_{12}^i; the strength of network effects for DF&Cs side gathering in the position j to FF&Cs side is α_{12}^j. The strength of network effects for FF&Cs side gathering in the position i to DF&Cs side is α_{21}^i; the strength of network effects for FF&Cs side gathering in the position j to DF&Cs side is α_{21}^j. Thus, the strength of network effects between groups is α_{12}^i, α_{12}^j, α_{21}^i, α_{21}^j. Under the premise of not influencing the analysis conclusion, we assume that the strength of network effects between groups is equal to α. Fourth, we assume that the reservation utility of side 1 DF&Cs takes the position i as their operating location is $\overline{u}_1^i$; the reservation utility of side 1 DF&Cs takes the position j as their operating location is $\overline{u}_1^j$; the reservation utility of side 2 FF&Cs takes the position i as their operating location is $\overline{u}_2^i$; the reservation utility of side 2 FF&Cs takes the position j as their operating location is $\overline{u}_2^j$. For side 2 FF&Cs, the function of taking l ($l \in \{i, j\}$) position as their operating location can be separated into the function of quality m and the function of price k, because the FF&Cs are maybe multihoming. Only multifunction can lead to multihoming. There is no necessary to separate the function of DF&Cs into quality function and price function because the DF&Cs side is single-homing. Accordingly, $\overline{u}_2^i = \overline{u}_{2m}^i + \overline{u}_{2k}^i$, $\overline{u}_2^j = \overline{u}_{2m}^j + \overline{u}_{2k}^j$ (where $\overline{u}_{2m}^i$ is the utility of quality function m of side 2 FF&Cs that take the position i as their operating location; $\overline{u}_{2m}^j$ is the utility of quality function m of side 2 FF&Cs that take the position j as their operating

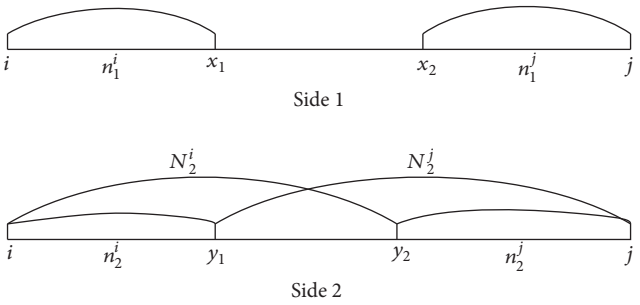

Figure 2: Model (I): Competitive Model on A Zone.

location; $\overline{u}_{2k}^i$ is the utility of price function k of side 2 FF&Cs that take the position i as their operating location; $\overline{u}_{2k}^j$ is the utility of price function k of side 2 FF&Cs that take the position j as their operating location). According to the actual situation, $\overline{u}_{2m}^i > \overline{u}_{2m}^j$, $\overline{u}_{2k}^j > \overline{u}_{2k}^i$. (For Tianjin is more big and international than Dalian, its service quality is high compared to Dalian, but Dalian can provide a lower service price.) p_1^i, p_1^j represent the cost (price) of DF&Cs that take the positions i, j as their operating location, respectively.

3. Model (I): Competitive Model on A Zone

The market is an oligopoly competition market when the North area and the South area are competing for the firms and consumers from A zone. For the North area, Model (I) diagram is shown as in Figure 2. In oligopoly competition market, the DF&Cs can choose to take the North area or the South area as their operating location. In this model the DF&Cs in $[x_1, x_2]$ do not take the North area as their operating location; they take the South area as their operating location.

Description of the notations in Figure 2 is as follows: i: Tianjin; j: Dalian; n_1^i: the DF&Cs who take position i as their operating location; x_1: the edge DF&Cs; n_1^j: the DF&Cs who take position j as their operating location; x_2: the edge DF&Cs; n_2^i: the FF&Cs who take position i as their operating location only; y_1: the edge FF&Cs; N_2^i: the FF&Cs who take position i only or take positions i, j as their operating location; y_2: the edge FF&Cs; n_2^j: the FF&Cs who take position j as their operating location only; y_2:the edge FF&Cs; N_2^j: the FF&Cs who take position j only or take positions i, j as their operating location; y_1: the edge FF&Cs.

The utility of the DF&Cs who take position i as their operating location is

$$u_1^i = \overline{u}_1^i - p_1^i - tx_1 + \alpha y_2. \tag{1}$$

The utility of DF&Cs is 0 if the DF&Cs located between x_1 and x_2, and the DF&Cs will take the South area as their operating location. So

$$\overline{u}_1^i - p_1^i - tx_1 + \alpha y_2 = 0. \tag{2}$$

The utility of the DF&Cs who take position j as their operating location is

$$u_1^j = \overline{u}_1^j + \alpha(1 - y_1) - t(1 - x_2) - p_1^j. \tag{3}$$

The utility of DF&Cs is 0 if the DF&Cs located between x_1 and x_2, and the DF&Cs will take the South area as their operating location. So

$$\overline{u}_1^j + \alpha(1 - y_1) - t(1 - x_2) - p_1^j = 0. \tag{4}$$

The utility of the FF&Cs who take position i as their operating location is

$$u_2^i = \overline{u}_2^i + \alpha x_1 - ty_1. \tag{5}$$

The utility of the FF&Cs who take positions i and j as their operating locations is

$$u_2^{ij} = \overline{u}_{2m}^i + \overline{u}_{2k}^j + \alpha[x_1 + (1 - x_2)] - t. \tag{6}$$

The utility of the FF&Cs who take position j as their operating location is

$$u_2^j = \overline{u}_{2m}^j + \overline{u}_{2k}^j + \alpha(1 - x_2) - t(1 - y_2). \tag{7}$$

Let $V_1^d = \overline{u}_1^i - \overline{u}_1^j$, $V_2^d = \overline{u}_{2k}^j - \overline{u}_{2k}^i + \overline{u}_{2m}^i - \overline{u}_{2m}^j$, $V_{2k}^d = \overline{u}_{2k}^j - \overline{u}_{2k}^i$, $V_{2m}^d = \overline{u}_{2m}^i - \overline{u}_{2m}^j$.

At point y_1, the FF&Cs who take position i as their operating locations or take positions i and j as their operating locations are indifferent. So

$$\begin{aligned} &u_2^i = u_2^{ij}, \\ &\overline{u}_2^i + ax_1 - ty_1 = \overline{u}_{2m}^i + \overline{u}_{2k}^j + a[x_1 + (1 - x_2)] - t. \end{aligned} \tag{8}$$

Simplifying this function, we can get

$$y_1 = \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j}{t} - \frac{a}{t} + \frac{ax_2}{t} + 1. \tag{9}$$

At point y_2, the FF&Cs who take position j as their operating locations or take positions i and j as their operating locations are indifferent. So

$$\begin{aligned} &u_2^j = u_2^{ij}, \\ &\overline{u}_{2m}^j + \overline{u}_{2k}^j + a(1 - x_2) - t(1 - y_2) \\ &\quad = \overline{u}_{2m}^i + \overline{u}_{2k}^j + a[x_1 + (1 - x_2)] - t. \end{aligned} \tag{10}$$

Simplifying this function, we can get

$$y_2 = \frac{\overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{ax_1}{t}. \tag{11}$$

Substituting (11) into (2), we can get

$$\overline{u}_1^i + a\left(\frac{\overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{ax_1}{t}\right) - tx_1 - p_1^i = 0. \tag{12}$$

Simplifying this function, we can get

$$x_1 = \frac{t}{t^2 - a^2}\left[\overline{u}_1^i - p_1^i + \frac{a\left(\overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{t}\right]. \quad (13)$$

From Figure 2, we know that

$$x_1 = n_1^i. \quad (14)$$

So

$$n_1^i = \frac{t}{t^2 - a^2}\left[\overline{u}_1^i - p_1^i + \frac{a\left(\overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{t}\right]. \quad (15)$$

Substituting (9) into (4), we can get

$$\overline{u}_1^j + a\left(\frac{a}{t} - \frac{ax_2}{t} - \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j}{t}\right) - t + tx_2 - p_1^j = 0. \quad (16)$$

Simplifying this function, we can get

$$x_2 = 1 - \frac{t}{t^2 - a^2}\left[\overline{u}_1^j - p_1^j - \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j\right)}{t}\right]. \quad (17)$$

From Figure 2, we know that

$$n_1^j = 1 - x_2. \quad (18)$$

So

$$n_1^j = \frac{t}{t^2 - a^2}\left[\overline{u}_1^j - p_1^j - \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j\right)}{t}\right]. \quad (19)$$

Profit function is

$$\pi = n_1^i \cdot p_1^i + n_1^j \cdot p_1^j = \frac{t}{t^2 - \alpha^2}\left[\overline{u}_1^i p_1^i - \left(p_1^i\right)^2 + \frac{\alpha V_{2m}^d}{t} p_1^i + \overline{u}_1^j p_1^j - \left(p_1^j\right)^2 + \frac{\alpha V_{2k}^d}{t} p_1^j\right]. \quad (20)$$

π is the function of (p_1^i, p_1^j), take the first-order derivative of p_1^i and p_1^j, and the reaction functions are

$$\frac{\partial \pi}{\partial p_1^i} = \frac{t}{t^2 - \alpha^2}\left(\overline{u}_1^i - 2p_1^i + \frac{aV_{2m}^d}{t}\right),$$
$$\frac{\partial \pi}{\partial p_1^j} = \frac{t}{t^2 - \alpha^2}\left(\overline{u}_1^j - 2p_1^j + \frac{aV_{2k}^d}{t}\right). \quad (21)$$

Let the reaction functions be zero, and the Bertrand-Nash equilibrium prices are

$$p_1^i = \frac{1}{2}\overline{u}_1^i + \frac{\alpha}{2t}V_{2m}^d, \quad (22)$$

$$p_1^j = \frac{1}{2}\overline{u}_1^j + \frac{\alpha}{2t}V_{2k}^d. \quad (23)$$

When $t > \alpha$, $\partial\pi^2/\partial(p_1^i)^2 < 0$, $\partial\pi^2/\partial(p_1^j)^2 < 0$, p_1^i and p_1^j are the solutions when π is maximization.

Lemma 1. *The user scale of the DF&Cs who take position i as their operating location is* $n_1^i = (t/2(t^2-\alpha^2))[\overline{u}_1^i+(\alpha/t)V_{2m}^d]$, *the user scale of the DF&Cs who take position j as their operating location is* $n_1^j = (t/2(t^2 - \alpha^2))[\overline{u}_1^j + (\alpha/t)V_{2k}^d]$, *the user scale of the FF&Cs who take position i only or take positions i, j as their operating location is* $N_2^i = V_{2m}^d/t + (\alpha/2(t^2 - \alpha^2))[\overline{u}_1^i + (\alpha/t)V_{2m}^d]$, *the user scale of the FF&Cs who take position j only or take positions i, j as their operating location is* $N_2^j = V_{2k}^d/t + (\alpha/2(t^2 - \alpha^2))[\overline{u}_1^j + (\alpha/t)V_{2k}^d]$, *the cost (price) of DF&Cs who take the position i as their operating location is* $p_1^i = (1/2)\overline{u}_1^i + (\alpha/2t)V_{2m}^d$, *the cost (price) of DF&Cs who take the position j as their operating location is* $p_1^j = (1/2)\overline{u}_1^j + (\alpha/2t)V_{2k}^d$, *and the total income of the North area is* $\pi = (t/4(t^2 - \alpha^2))[(\overline{u}_1^i + (\alpha/t)V_{2m}^d)^2 + (\overline{u}_1^j + (\alpha/t)V_{2k}^d)^2]$.

Proof. According to formula (15), $n_1^i = (t/(t^2 - a^2))[\overline{u}_1^i - p_1^i + a(\overline{u}_{2m}^i - \overline{u}_{2m}^j)/t]$; substitute formula (22) into it. Simplify it; then we can get $n_1^i = (t/2(t^2 - \alpha^2))[\overline{u}_1^i + (\alpha/t)V_{2m}^d]$.

According to formula (19), $n_1^j = (t/(t^2 - a^2))[\overline{u}_1^j - p_1^j - a(\overline{u}_{2k}^i - \overline{u}_{2k}^j)/t]$; substitute formula (23) into it. Simplify it; then we can get $n_1^j = (t/2(t^2 - \alpha^2))[\overline{u}_1^j + (\alpha/t)V_{2k}^d]$.

From Figure 2, we know that

$$N_2^i = y_2. \quad (24)$$

According to formula (11),

$$y_2 = \frac{\overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{ax_1}{t}. \quad (25)$$

We also know that $x_1 = n_1^i$; substitute $n_1^i = (t/2(t^2 - \alpha^2))[\overline{u}_1^i + (\alpha/t)V_{2m}^d]$ into formula (11). Simplify it; then we can get

$$N_2^i = \frac{V_{2m}^d}{t} + \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left[\overline{u}_1^i + \frac{\alpha}{t}V_{2m}^d\right]. \quad (26)$$

From Figure 2, we know that

$$N_2^j = 1 - y_1. \quad (27)$$

According to formula (11)

$$y_1 = \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j}{t} - \frac{a}{t} + \frac{ax_2}{t} + 1. \quad (28)$$

We also know that $x_2 = 1 - n_1^j$; substitute $n_1^j = (t/2(t^2 - \alpha^2))[\overline{u}_1^j + (\alpha/t)V_{2k}^d]$ into formula (9). Simplify it; then we can get

$$N_2^j = \frac{V_{2k}^d}{t} + \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left[\overline{u}_1^j + \frac{\alpha}{t}V_{2k}^d\right]. \quad (29)$$

According to formulae (22) and (23), $p_1^i = (1/2)\overline{u}_1^i + (\alpha/2t)V_{2m}^d$ and $p_1^j = (1/2)\overline{u}_1^j + (\alpha/2t)V_{2k}^d$.

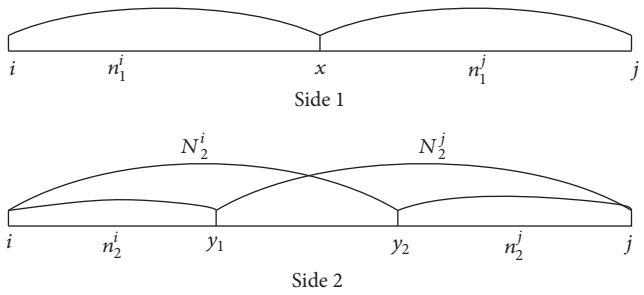

Figure 3: Model (II): Competitive Model on B Zone.

Substituting formulae (22) and (23) into formula (20) and simplify them, we can get

$$\pi = \frac{t}{4\left(t^2-\alpha^2\right)}\left[\left(\overline{u}_1^i + \frac{\alpha}{t}V_{2m}^d\right)^2 + \left(\overline{u}_1^j + \frac{\alpha}{t}V_{2k}^d\right)^2\right]. \quad (30)$$

□

4. Model (II): Competitive Model on B Zone

When x_1 overlaps with x_2, Model (II) diagram is shown as in Figure 3. The utility of the DF&Cs who take position i as their operating location is

$$u_1^i = \overline{u}_1^i - p_1^i - tx + \alpha N_2^i. \quad (31)$$

The utility of the DF&Cs who take position j as their operating location is

$$u_1^j = \overline{u}_1^j - p_1^j - t(1-x) + \alpha N_2^j. \quad (32)$$

The utility of the FF&Cs who take position i as their operating location is

$$u_2^i = \overline{u}_2^i + \alpha n_1^i - ty_1. \quad (33)$$

The utility of the FF&Cs who take both positions i and j as their operating location is

$$u_2^{ij} = \overline{u}_{2m}^i + \overline{u}_{2k}^j + \alpha - t. \quad (34)$$

The utility of the FF&Cs who take position j as their operating location is

$$u_2^j = \overline{u}_2^j + \alpha n_1^j - t(1-y_2). \quad (35)$$

At point x, the DF&Cs who take position i or j as their operating location are indifferent. So

$$\begin{aligned} u_1^i &= u_1^j \\ \overline{u}_1^i + aN_2^i - p_1^i - tx &= \overline{u}_1^j + aN_2^j - p_1^j - t(1-x). \end{aligned} \quad (36)$$

Solving it,

$$x = \frac{1}{2} + \frac{\overline{u}_1^i - \overline{u}_1^j}{2t} + \frac{a\left(N_2^i - N_2^j\right)}{2t} + \frac{p_1^j - p_1^i}{2t}. \quad (37)$$

From Figure 3, we know that

$$n_1^i = x. \quad (38)$$

So

$$n_1^i = \frac{1}{2} + \frac{\overline{u}_1^i - \overline{u}_1^j}{2t} + \frac{a\left(N_2^i - N_2^j\right)}{2t} + \frac{p_1^j - p_1^i}{2t}. \quad (39)$$

At point y_1, the FF&Cs who take position i or positions i and j as their operating location are indifferent. So

$$\begin{aligned} u_2^i &= u_2^{ij}, \\ \overline{u}_2^i + an_1^i - ty_1 &= \overline{u}_{2m}^i + \overline{u}_{2k}^j + a - t. \end{aligned} \quad (40)$$

Solving it,

$$y_1 = 1 + \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j}{t} - \frac{a}{t}n_1^j. \quad (41)$$

From Figure 3, we know that

$$n_2^i = y_1. \quad (42)$$

So

$$n_2^i = 1 + \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j}{t} - \frac{a}{t}n_1^j. \quad (43)$$

At point y_2, the FF&Cs who take position j or positions i and j as their operating location are indifferent. So

$$\begin{aligned} u_2^{ij} &= u_2^j, \\ \overline{u}_{2m}^i + \overline{u}_{2k}^j + a - t &= \overline{u}_2^j + an_1^j - t(1-y_2). \end{aligned} \quad (44)$$

Solving it,

$$y_2 = \frac{\overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{an_1^i}{t}. \quad (45)$$

From Figure 3, we know that

$$\begin{aligned} n_2^j &= 1 - y_2, \\ n_2^j &= 1 + \frac{\overline{u}_{2m}^j - \overline{u}_{2m}^i}{t} - \frac{a}{t}n_1^i. \end{aligned} \quad (46)$$

Because $n_2^i + N_2^j = 1$ and $n_2^j + N_2^i = 1$, $N_2^j = 1 - n_2^i$ and $N_2^i = 1 - n_2^j$. So $N_2^i - N_2^j = (1 - n_2^j) - (1 - n_2^i) = n_2^i - n_2^j$. Because $n_1^i + n_1^j = 1$, $n_1^j = 1 - n_1^i$.

Substituting $N_2^i - N_2^j$ into formula (39), we can get

$$n_1^i = \frac{1}{2} + \frac{\overline{u}_1^i - \overline{u}_1^j}{2t} + \frac{a\left(n_2^i - n_2^j\right)}{2t} + \frac{p_1^j - p_1^i}{2t}. \quad (47)$$

Because $n_2^i - n_2^j = (\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j)/t + a(n_1^i - n_1^j)/t$, $n_1^i - n_1^j = n_1^i - 1 + n_1^i = 2n_1^i - 1$.

So

$$n_2^i - n_2^j = \frac{\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{a}{t}\left(2n_1^i - 1\right). \quad (48)$$

Substitute formula (48) into formula (47). Solving it, we can get

$$n_1^i = \frac{1}{2} + \frac{t\left(\overline{u}_1^i - \overline{u}_1^j\right)}{2\left(t^2 - a^2\right)} + \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{2\left(t^2 - a^2\right)} + \frac{t\left(p_1^j - p_1^i\right)}{2\left(t^2 - a^2\right)}. \quad (49)$$

Because $n_1^j = 1 - n_1^i$,

$$n_1^j = \frac{1}{2} - \frac{t\left(\overline{u}_1^i - \overline{u}_1^j\right)}{2\left(t^2 - a^2\right)} - \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{2\left(t^2 - a^2\right)} - \frac{t\left(p_1^j - p_1^i\right)}{2\left(t^2 - a^2\right)}. \quad (50)$$

Profit functions are

$$\pi^i = n_1^i \cdot p_1^i = \left[\frac{1}{2} + \frac{tV_1^d}{2\left(t^2 - \alpha^2\right)} + \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right) + \frac{p_1^j t}{2\left(t^2 - \alpha^2\right)} - \frac{p_1^i t}{2\left(t^2 - \alpha^2\right)}\right] \cdot p_1^i,$$
$$\pi^j = n_1^j \cdot p_1^j = \left[\frac{1}{2} - \frac{t}{2\left(t^2 - \alpha^2\right)}V_1^d - \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right) - \frac{p_1^j t}{2\left(t^2 - \alpha^2\right)} + \frac{p_1^i t}{2\left(t^2 - \alpha^2\right)}\right] \cdot p_1^j \quad (51)$$

π^i is the function of p_1^i; take the first-order derivative of p_1^i; π^j is the function of p_1^j; take the first-order derivative of p_1^j; the reaction functions are

$$\frac{\partial \pi_1}{\partial p_1^i} = \frac{1}{2} + \frac{t}{2\left(t^2 - \alpha^2\right)}V_1^d + \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right) + \frac{p_1^j t}{2\left(t^2 - \alpha^2\right)} - \frac{p_1^i t}{\left(t^2 - \alpha^2\right)}, \quad (52)$$

$$\frac{\partial \pi_2}{\partial p_1^j} = \frac{1}{2} - \frac{t}{2\left(t^2 - \alpha^2\right)}V_1^d - \frac{\alpha}{2\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right) + \frac{p_1^i t}{2\left(t^2 - \alpha^2\right)} - \frac{p_1^j t}{\left(t^2 - \alpha^2\right)}. \quad (53)$$

Let the reaction functions be zero, respectively, and the Bertrand-Nash equilibrium prices are

$$p_1^i = \frac{t^2 - \alpha^2}{t} + \frac{1}{3}V_1^d + \frac{\alpha}{3t}\left(V_{2m}^d - V_{2k}^d\right),$$
$$p_1^j = \frac{t^2 - \alpha^2}{t} - \frac{1}{3}V_1^d - \frac{\alpha}{3t}\left(V_{2m}^d - V_{2k}^d\right). \quad (54)$$

When $t > \alpha$, $\partial\pi^2/\partial(p_1^i)^2 < 0$, $\partial\pi^2/\partial(p_1^j)^2 < 0$, p_1^i and p_1^j are the solutions when π is maximization.

Lemma 2. *The user scale of the DF&Cs who take position i as their operating location is* $n_1^i = 1/2 + (t/6(t^2 - \alpha^2))V_1^d + (\alpha/6(t^2 - \alpha^2))(V_{2m}^d - V_{2k}^d)$, *the user scale of the DF&Cs who take position j as their operating location is* $n_1^j = 1/2 - (t/6(t^2 - \alpha^2))V_1^d - (\alpha/6(t^2 - \alpha^2))(V_{2m}^d - V_{2k}^d)$, *the user scale of the FF&Cs who take position i only or take positions i, j as their operating location is* $N_2^i = \alpha/2t + V_{2m}^d/t + (\alpha/6(t^2 - \alpha^2))V_1^d + (\alpha^2/6t(t^2 - \alpha^2))(V_{2m}^d - V_{2k}^d)$, *the user scale of the FF&Cs who take position j only or take positions i, j as their operating location is* $N_2^j = \alpha/2t + V_{2k}^d/t - (\alpha/6(t^2 - \alpha^2))V_1^d - (\alpha^2/6t(t^2 - \alpha^2))(V_{2m}^d - V_{2k}^d)$, *the cost of DF&Cs who take the position i as their operating location is* $p_1^i = (t^2 - \alpha^2)/t + (1/3)V_1^d + (\alpha/3t)(V_{2m}^d - V_{2k}^d)$, *the cost of DF&Cs who take the position j as their operating location is* $p_1^j = (t^2 - \alpha^2)/t - (1/3)V_1^d - (\alpha/3t)(V_{2m}^d - V_{2k}^d)$, *and the total income of the North area is* $\pi = (t^2 - \alpha^2)/t + (t/9(t^2 - \alpha^2))[V_1^d + (\alpha/t)(V_{2m}^d - V_{2k}^d)]^2$.

Proof. According to formula (49),

$$n_1^i = \frac{1}{2} + \frac{t\left(\overline{u}_1^i - \overline{u}_1^j\right)}{2\left(t^2 - a^2\right)} + \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{2\left(t^2 - a^2\right)} + \frac{t\left(p_1^j - p_1^i\right)}{2\left(t^2 - a^2\right)}. \quad (55)$$

Substitute formula (54) into it and simplify it. We can get

$$n_1^i = \frac{1}{2} + \frac{t}{6\left(t^2 - \alpha^2\right)}V_1^d + \frac{\alpha}{6\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right). \quad (56)$$

According to formula (50),

$$n_1^j = \frac{1}{2} - \frac{t\left(\overline{u}_1^i - \overline{u}_1^j\right)}{2\left(t^2 - a^2\right)} - \frac{a\left(\overline{u}_{2k}^i - \overline{u}_{2k}^j + \overline{u}_{2m}^i - \overline{u}_{2m}^j\right)}{2\left(t^2 - a^2\right)} - \frac{t\left(p_1^j - p_1^i\right)}{2\left(t^2 - a^2\right)}. \quad (57)$$

Substitute formula (54) into it and simplify it. We can get

$$n_1^j = \frac{1}{2} - \frac{t}{6\left(t^2 - \alpha^2\right)}V_1^d - \frac{\alpha}{6\left(t^2 - \alpha^2\right)}\left(V_{2m}^d - V_{2k}^d\right). \quad (58)$$

From Figure 3, we know that

$$N_2^i = 1 - n_2^j. \quad (59)$$

According to formula (46),

$$N_2^i = \frac{\overline{u}_{2m}^i - \overline{u}_{2m}^j}{t} + \frac{a}{t} n_1^i. \tag{60}$$

Substitute formula (56) into it and simplify it. We can get

$$N_2^i = \frac{\alpha}{2t} + \frac{V_{2m}^d}{t} + \frac{\alpha}{6\left(t^2 - \alpha^2\right)} V_1^d + \frac{\alpha^2}{6t\left(t^2 - \alpha^2\right)} \left(V_{2m}^d - V_{2k}^d\right). \tag{61}$$

From Figure 3, we know that

$$N_2^j = 1 - n_2^i. \tag{62}$$

According to formula (43),

$$N_2^j = \frac{\overline{u}_{2k}^j - \overline{u}_{2k}^i}{t} + \frac{a}{t} n_1^j. \tag{63}$$

Substitute formula (58) into it and simplify it. We can get

$$N_2^j = \frac{\alpha}{2t} + \frac{V_{2k}^d}{t} - \frac{\alpha}{6\left(t^2 - \alpha^2\right)} V_1^d - \frac{\alpha^2}{6t\left(t^2 - \alpha^2\right)} \left(V_{2m}^d - V_{2k}^d\right). \tag{64}$$

According to formula (54), $p_1^i = (t^2 - \alpha^2)/t + (1/3)V_1^d + (\alpha/3t)(V_{2m}^d - V_{2k}^d)$ and $p_1^j = (t^2 - \alpha^2)/t - (1/3)V_1^d - (\alpha/3t)(V_{2m}^d - V_{2k}^d)$.

Substitute formula (54) into formula (51). Add them and simplify; we can get

$$\pi = \frac{\left(t^2 - \alpha^2\right)}{t} + \frac{t}{9\left(t^2 - \alpha^2\right)} \left[V_1^d + \frac{\alpha}{t}\left(V_{2m}^d - V_{2k}^d\right)\right]^2. \tag{65}$$

□

5. A Comparative Analysis of Model (I) and Model (II)

Under normal condition, the reservation utility of side 1 DF&Cs who take the position i as their operating locations $\overline{u}_1^i$ is much bigger than V_1^d which is the difference of the utility of DF&Cs who take the position i as their operating locations and the DF&Cs who take the position j as their operating locations. And $\overline{u}_1^i$ is much bigger than V_2^d which is the difference of the utility of FF&Cs who take the position i as their operating locations and the FF&Cs who take the position j as their operating locations. The relationships are also existing to $\overline{u}_1^j$, V_1^d and V_2^d. So we get Proposition 3.

Proposition 3. *Dalian and Tianjin should charge different price to the DF&Cs from zone A and zone B. And the price and total income of the two cities from zone A are higher than those from zone B.*

Proof. According to Lemmas 1 and 2, one has the following.

From zone A,

$$p_1^i = \frac{1}{2}\overline{u}_1^i + \frac{\alpha}{2t} V_{2m}^d,$$
$$p_1^j = \frac{1}{2}\overline{u}_1^j + \frac{\alpha}{2t} V_{2k}^d, \tag{66}$$
$$\pi = \frac{t}{4\left(t^2 - \alpha^2\right)} \left[\left(\overline{u}_1^i + \frac{\alpha}{t} V_{2m}^d\right)^2 + \left(\overline{u}_1^j + \frac{\alpha}{t} V_{2k}^d\right)^2\right].$$

From zone B,

$$p_1^i = \frac{t^2 - \alpha^2}{t} + \frac{1}{3} V_1^d + \frac{\alpha}{3t}\left(V_{2m}^d - V_{2k}^d\right),$$
$$p_1^j = \frac{t^2 - \alpha^2}{t} - \frac{1}{3} V_1^d - \frac{\alpha}{3t}\left(V_{2m}^d - V_{2k}^d\right), \tag{67}$$
$$\pi = \frac{\left(t^2 - \alpha^2\right)}{t} + \frac{t}{9\left(t^2 - \alpha^2\right)} \left[V_1^d + \frac{\alpha}{t}\left(V_{2m}^d - V_{2k}^d\right)\right]^2.$$

They are different and that means Dalian and Tianjin should charge different price in different zones.

$\overline{u}_1^i$ and $\overline{u}_1^j$ are the reservation utility of the two cities; they are absolute values. V_1^d, V_2^d, V_m^d, and V_k^d are the difference value. Under normal condition the difference values are much smaller than the absolute values. So the price and total income of the two cities from zone A are higher than those from zone B. □

Proposition 4. *When the intensity of cross network effects between the two-sided users increases, the cost of DF&Cs from zone A who take Dalian and Tianjin as operating locations and the total income of the North area from zone A will be increased accordingly.*

Proof.

$$\frac{\partial p_1^i}{\partial \alpha} = \frac{V_{2m}^d}{2t} > 0,$$
$$\frac{\partial p_1^j}{\partial \alpha} = \frac{V_{2k}^d}{2t} < 0,$$
$$\frac{\partial \pi}{\partial \alpha} = \frac{\left(t\overline{u}_1^i + \alpha V_{2m}^d\right)\left(\alpha\overline{u}_1^i + tV_{2m}^d\right) + \left(t\overline{u}_1^j + \alpha V_{2k}^d\right)\left(\alpha\overline{u}_1^j + tV_{2k}^d\right)}{2\left(t^2 - \alpha^2\right)^2} \tag{68}$$
$$> 0.$$

So the North area can take measures to increase the intensity between cross network effects of two-sided users in order to increase the viscosity between two-sided users and to improve the service experience of two-sided users. Ultimately it can improve the revenue of Dalian and Tianjin. □

Table 1: The set of the characters and the results.

Characters	Situation 1		Situation 2		Situation 3		Situation 4	
	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A	Zone B
$\overline{u}_1^i$	10.000	10.000	10.000	10.000	10.000	10.000	10.000	10.000
$\overline{u}_1^j$	9.500	9.500	9.500	9.500	9.500	9.500	9.500	9.500
$\overline{u}_{2m}^i$	1.250	1.250	1.250	1.250	2.050	2.050	1.250	1.250
$\overline{u}_{2m}^j$	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\overline{u}_{2k}^i$	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
$\overline{u}_{2k}^j$	1.200	1.200	1.200	1.200	1.200	1.200	1.300	1.300
t	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
a	0.300	0.300	0.500	0.500	0.300	0.300	0.300	0.300
p_1^i	5.038	1.122	5.063	0.992	5.158	1.202	5.038	1.132
p_1^j	4.780	0.698	4.800	0.508	4.780	0.618	4.795	0.688
π	52.994	0.959	64.892	0.828	54.339	1.003	53.152	0.964

When the differences of quality utility V_{2m}^d and price utility V_{2k}^d for the FF&Cs who take positions i and j as their operating locations increase, the price and total income of the North area will be increased accordingly. So we get Proposition 5.

Proposition 5. *When the differences of quality utility and price utility increase, the price of the DF&Cs from zone A who take North area as their operating locations and the income of the North area from zone A will be increased.*

Proof.

$$\begin{aligned}
\frac{\partial p_1^i}{\partial V_{2m}^d} &= \frac{\alpha}{2t} > 0,\\
\frac{\partial p_1^j}{\partial V_{2k}^d} &= \frac{\alpha}{2t} > 0,\\
\frac{\partial \pi}{\partial V_{2m}^d} &= \frac{t\alpha\overline{u}_1^i + \alpha^2 V_{2m}^d}{2t\,(t-\alpha)\,(t+\alpha)},\\
\frac{\partial \pi}{\partial V_{2k}^d} &= \frac{t\alpha\overline{u}_1^j + \alpha^2 V_{2k}^d}{2t\,(t-\alpha)\,(t+\alpha)}.
\end{aligned} \tag{69}$$

When $t > \alpha$, then we can get: $\partial\pi/\partial V_{2m}^d > 0$, $\partial\pi/\partial V_{2k}^d > 0$. □

The North area can arrange service with bigger difference of quality on Dalian and Tianjin, respectively, so the North area can get more income. For example, compared with providing the same service in Dalian and Tianjin providing difference services in Dalian and Tianjin, the quality utility of the latter is better than the former, and the North area (both Dalian and Tianjin) can get more income.

6. Numerical Example

Suppose Dalian and Tianjin face four situations; the set of the characters and the results are shown in Table 1.

Comparing the results of zone A and zone B, p_1^i, p_1^j, and π are different, and the former is higher than the latter. So Proposition 3 is confirmed.

Comparing the results of Situation 1-zone A and Situation 2-zone A with the increasing of a, p_1^i, p_1^j, and π are increasing.

Comparing the results of Situation 1-zone A and Situation 3-zone A with the increasing of V_{2m}^d, p_1^i, p_1^j, and π are increasing. Comparing the results of Situation 1-zone A and Situation 4-zone A with the increasing of V_{2k}^d, p_1^i, p_1^j, and π are increasing. So Proposition 5 is confirmed.

7. Conclusion

Based on the two-sided markets this paper built two theoretical models to analyze the competitive strategy of cross-border e-commerce comprehensive pilot areas of Dalian and Tianjin of the North area. Through the equilibrium results of comparative static analysis, this article draws the following conclusions.

(1) Dalian and Tianjin should charge different price to the DF&Cs from zone A and zone B. And the price and total income of the two cities from zone A are higher than those from zone B.

(2) The strength of network effects between groups will affect the revenue of the North area. The greater the network effect is, the greater the revenue of the North area will be.

(3) When the FF&Cs take the North area as the operating location, the difference of the quality utility and the difference of the price utility impact the revenue of the North area. The greater the difference in the quality utility or price utility is, the greater the income of the North area will be.

But there are still some shortcomings of this model. First, this model is a theory model; it is hard to use in practice. The characters should be collected and evaluated. Second some assumptions are too strict; for example, the DF&Cs from C and D zones may not choose Dalian or Tianjin as their operation location. Also DF&Cs in zone B may also choose

other cross-border e-commerce comprehensive pilot areas as their operation location.

Even though the model still casts same managerial implications to us,

(1) in order to maximize their revenue, Dalian and Tianjin should charge different price for the DF&Cs from different zones;

(2) in order to increase the revenue from zone A, the cities can increase the network effects a, the difference of quality utility V_{2m}^{d}, and the price utility V_{2k}^{d}.

Future research: in this article South area is set exogenous, in the future research we can make it endogenous in the model. Another possible direction is to verify the model proposed in this article through simulation.

Competing Interests

The authors declare that they have no competing interests.

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Research Article

Optimal Uncertainty Decision of Innovation Products Output Based on Return Collection

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As the length of time between product renewals decreases, the enterprises that make innovative products face new challenges. The production cost structure of innovative products can be changed by collecting product returns, which can be economically valuable for enterprises. Enterprises face both production and demand randomness; hence, it is important to improve the traditional optimal production decision-making model that considers the randomness of demand only. This paper divides innovative products into structural innovation products and improved innovation products. The paper studies the optimal single-period production decision between reused parts and conventional new parts in complementary and substitute relationships. It further gives the analytical expressions for satisfying the optimal production and provides some numerical examples. The research results indicate that when producing innovative products, whether based on structural or improved innovation, with the variance of the quantity of the recycled parts increasing, the optimal purchase quantity of the conventional parts will increase but the expected profits for the innovative products will decrease. With integrated substitution and complementation based on improved innovation, enhancing the fluctuation in the number of recycled parts has a greater impact on the optimal purchase quantity of the substitute conventional parts than that of the complementary parts.

1. Introduction

The product production process is key to reducing an enterprise's inventory and to improving enterprise profitability, and there is much research on this issue. The accuracy of product output decisions has a significant impact on profitability. Some studies show that market demand uncertainty is a major factor in causing inaccurate output decisions in semiconductor manufacturing enterprises [1–3] and in seasonal product enterprises [4]. Decision-making models show that enterprises can establish an optimal output decision model in which market demand is in line with the normal distribution [4] based on the penalty coefficient of the market share and employee factors [5], on integration with the Monte-Carlo simulation method and a genetic algorithm, and on optimizing the product output [6, 7]. Other studies investigate production in a multistage manufacturing system and in a three-stage supply chain made up of multiple suppliers, multiple manufacturers, and multiple markets [8] and use dynamic programming and recursive algorithms to determine the optimal production strategy at each stage [9] and the optimal distribution of the production of different products [10]. In addition to considering the impact of market demand, some studies consider the impact of defective products on production decisions [11, 12], especially for clothing, leather, stationery, and other traditional industries [13]. Based on whether product production is a multistage manufacturing system or a different production mode [9, 14–21], it is necessary to consider remanufacturing costs, inventory costs, and shortage costs [22, 23] and to make decisions in production planning and in production output when studying remanufacturing lot-sizing problems under an uncertain environment [24–27]. Worker errors [28, 29], machine breakdowns, and product rejects [30] can all cause defective products. The defective rate can be predicted using a support vector machine model based on statistical learning

theory [31]. Using order production based on capacity constraints [11, 32], inventory control, and other methods [33, 34], enterprises can model and optimize their decisions on planning the quantity of products to produce [13, 35–39].

Traditionally, studies on enterprise management decisions focus on the cost optimization, enterprise production, inventory, and purchase decisions. As the product lifecycle becomes increasingly shorter, the amount of waste products generated has an increasingly serious impact on the environment. It is difficult for the innovative enterprise to balance enterprise development and environmental protection. The former strategy focuses on profit growth, while the latter focuses on sustainable development. Now, many enterprises must develop a product recycling strategy. Using recycled parts changes the enterprise cost structure. Such reuse can both meet environmental laws and other requirements and bring potential economic benefits. Generally, product output decisions do not account for the influence of recycled parts, an issue known as product reverse logistics [40]. Product reverse logistics means studying product output decisions while considering remanufacturing recycled products. Recycling for reuse is complex [41]. Considerations include the fixed-cost split between reuse and manufacturing [42], grading the recycled products to move from qualitative to quantitative production [43], and studying the interaction between manufacturing and reuse using a mixed integer linear programming model [44]. For production planning when reusing parts, it is necessary to consider the correlation between the parts [45] and the demand for shared parts by different products [46]. Hence, it is important to analyze the material recoverability rates when parts are dismantled [47], the remanufacturing rate, and the uncertainty of technology process [48]. The remanufacturing production planning is determined based on a production planning and scheduling model and state equation [49].

There are many decision-making studies on traditional product production. However, few studies focus on decisions relating to innovative product production. Unlike traditional products, enterprises often use new parts to produce innovative products. Innovative products are generally characterized by a short lifecycle and by rapid replacement. This situation generates a lot of waste, which is costly for the enterprises. Previous enterprise innovation studies do not have a micro focus, but rather they consider aspects such as the innovation preprocess and the relationship between innovation and enterprise performance. Those studies that investigate the commercialization process of innovation focus on the macro characteristics only, such as the impact of new products on the economy. This paper explores uncertainty decisions based on the innovative product output using recycled parts from a relatively micro perspective. Hence, under the uncertainty condition of the recycling of remanufacturing components, this paper considers the coordination between remanufacturing and new components.

2. Model Assumption and Construction

2.1. Model Assumption. The model assumes the following. The production, sales, recycling, and other relevant functions are accomplished independently by one enterprise. The enterprise is a centralized decision-making system. The cost of the recycled parts is C_r. The cost of the substitutive conventional parts is C_s. The cost of the complementary conventional parts is C_c.

The lifecycle of the innovative products is short. If such products have not sold out in a certain time period, then it is generally considered as an innovation failure. When the production exceeds the demand, the penalty value for each product is s. If the supply is inadequate to meet the demand, then it is generally considered as an innovation success. Demand fluctuation is represented by random variable D. The distribution function and the probability density function of D are $F(\cdot)$ and $f(\cdot)$, respectively.

The number of recycled parts, represented by random variable R, cannot be accurately forecasted by the enterprises. The distribution function and the probability density function of R are $F_R(\cdot)$ and $f_R(\cdot)$, respectively, independent of D. The enterprises cannot be artificially manipulated. The parameters do not change over time.

2.2. Model Construction. The enterprises that make innovative products use two methods: structural innovation and improved innovation. The products based on structural innovation are new products that are regrouped from existing parts. The products based on improved innovation are new products that require both old parts and some new parts. These two methods show that there is a substitutability or a complementary relationship between recycled parts and conventional new parts when the enterprises produce the innovative products. Under a substitutability condition, the innovative products are produced using recycled parts or using new parts purchased conventionally. Under a complementary condition, the innovative products are produced using both recycled parts and new parts purchased conventionally. Both are indispensable. This paper focuses on making decisions to optimize the profits of the enterprises that produce innovative products using these two methods.

(1) Part Substitution Based on Structural Innovation. If the number of recycled parts is R and decision variable q is the number of conventional new parts purchased by the enterprises (determined before R), then the final actual output is $R + q$. The output is obtained according to random demand D, and then sales revenue and cost are generated [50]. Here, the expected profit for the enterprise in producing innovative products is

$$\begin{aligned} &E(\Pi_1) \\ &= E\left(p\min(R+q, D) - c_s q - c_r R - s(R+q-D)^+\right). \end{aligned} \tag{1}$$

The following function is defined:

$$(x)^+ = \begin{cases} x, & x \geq 0, \\ 0, & x < 0. \end{cases} \tag{2}$$

Figure 1 illustrates the relationship between actual demand D and number of recovered parts R.

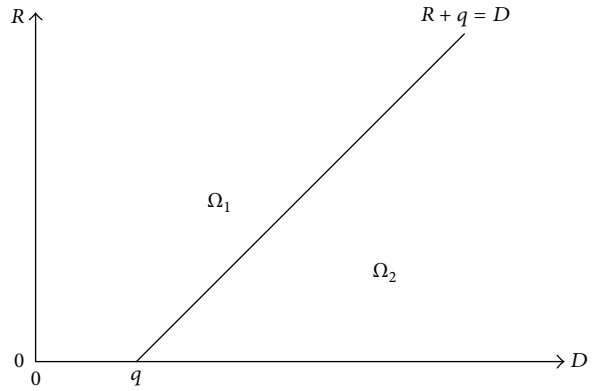

Figure 1: Relationship between demand D and the number of recovered parts R.

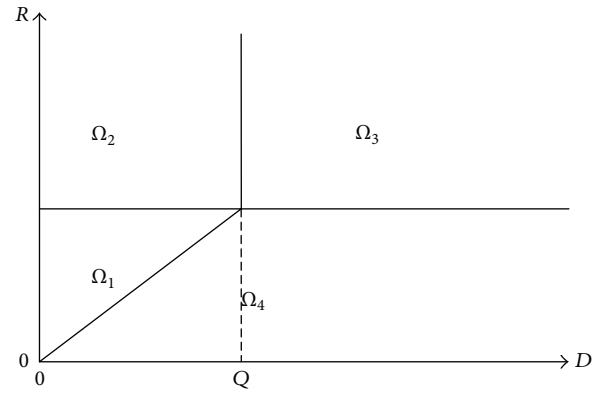

Figure 2: Relationship between demand D and the number of recovered parts R.

Here, according to the division shown in Figure 1, the profit function can be expressed as

$$\Pi_1 = \begin{cases} pD - c_s q - c_r R - s\left(R + q - D\right), & (R, D) \in \Omega_1, \\ p\left(R + q\right) - c_s q - c_r R, & (R, D) \in \Omega_2. \end{cases} \quad (3)$$

(2) Part Complementarity Based on Improved Innovation. If the number of recycled parts is R and decision variable Q is the number of conventional new parts purchased by the enterprises (determined before R), then the final actual output is $\min(Q, R)$. The output is obtained according to random demand D, and then sales revenue and cost are generated. Here, the expected profit for the enterprise in producing innovative products is

$$E\left(\Pi_2\right) = E\left(p \min\left(\min\left(Q, R\right), D\right) - c_c Q - c_r R - s\left(\min\left(Q, R\right) - D\right)^+\right). \quad (4)$$

Here, actual demand D and number of recovered parts R can be divided into four separate areas, as shown in Figure 2.

Here, according to the division in Figure 2, the profit function can be expressed as

$$\Pi_2 = \begin{cases} pD - c_c Q - c_r R - s\left(R - D\right), & (R, D) \in \Omega_1, \\ pD - c_c Q - c_r R - s\left(Q - D\right), & (R, D) \in \Omega_2, \\ pQ - c_c Q - c_r R, & (R, D) \in \Omega_3, \\ pR - c_c Q - c_r R, & (R, D) \in \Omega_4. \end{cases} \quad (5)$$

(3) Integrated Substitution and Complementarity Model Based on Improved Innovation. If the number of recycled parts is R and the decision variables q and Q are the number of substitute and complementary conventional new parts, respectively, purchased by the enterprises (determined before R), then the final actual output is $\min(Q, R + q)$. The output is obtained according to random demand D, and then sales revenue and cost are generated. Here, the expected profit for the enterprise in producing innovative products is

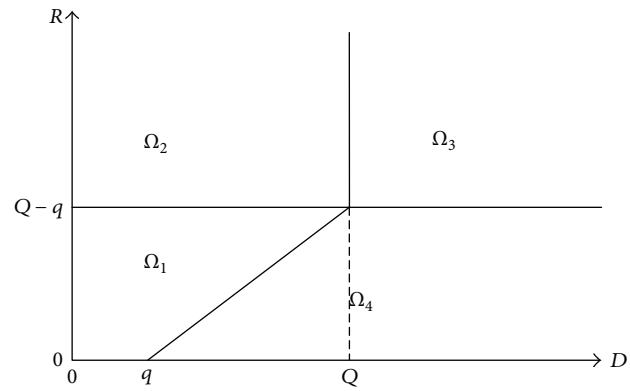

Figure 3: Relationship between demand D and the number of recovered parts R.

$$E\left(\Pi_3\right) = E\left(p \min\left(\min\left(Q, R + q\right), D\right) - c_c Q - c_s q - c_r R - s\left(\min\left(Q, R + q\right) - D\right)^+\right). \quad (6)$$

Here, actual demand D and number of recovered parts R can be divided into four separate areas, as shown in Figure 3.

Here, according to the division in Figure 3, the profit function can be expressed as

$$\Pi_3 = \begin{cases} pD - c_c Q - c_s q - c_r R - s\left(R + q - D\right), & (R, D) \in \Omega_1, \\ pD - c_c Q - c_s q - c_r R - s\left(Q - D\right), & (R, D) \in \Omega_2, \\ pQ - c_c Q - c_s q - c_r R, & (R, D) \in \Omega_3, \\ p\left(R + q\right) - c_c Q - c_s q - c_r R, & (R, D) \in \Omega_4. \end{cases} \quad (7)$$

3. Model Solution

3.1. Optimal Decision for Part Substitution Based on Structural Innovation. The profit function can be expressed as

$$\Pi_1 = \begin{cases} pD - c_s q - c_r R - s\left(R + q - D\right), & (R, D) \in \Omega_1, \\ p\left(R + q\right) - c_s q - c_r R, & (R, D) \in \Omega_2. \end{cases} \quad (8)$$

Thus, the expected profit $E(\Pi_1)$ is

$$\begin{aligned} E\left(\Pi_1\right) &= \iint_{\Omega_1 \cup \Omega_2} \Pi_1 f_D\left(D\right) f_R\left(R\right) d\Omega \\ &= \iint_{\Omega_1} \left[pD - c_s q - c_r R - s\left(R + q - D\right)\right] f_D\left(D\right) \\ &\cdot f_R\left(R\right) d\Omega + \iint_{\Omega_2} \left[p\left(R + q\right) - c_s q - c_r R\right] \\ &\cdot f_D\left(D\right) f_R\left(R\right) d\Omega. \end{aligned} \quad (9)$$

In this formula, $\iint_{\Omega_1} [pD - c_s q - c_r R - s(R + q - D)] f_D(D) f_R(R) d\Omega$ is the expected profit of the enterprise when R and D intersection falls in area Ω_1 in Figure 1. Further, $\iint_{\Omega_2} [p(R+q) - c_s q - c_r R] f_D(D) f_R(R) d\Omega$ is the expected profit of the enterprise when R and D intersection falls in area Ω_2 in Figure 1 [50].

So, we can get

$$\begin{aligned} E\left(\Pi_1\right) &= p \iint_{\Omega_1} f_D\left(D\right) f_R\left(R\right) d\Omega \\ &+ p \iint_{\Omega_1} \left(R + q\right) f_D\left(D\right) f_R\left(R\right) d\Omega - c_s q \\ &- c_r \iint_{\Omega_1 \cup \Omega_2} R f_D\left(D\right) f_R\left(R\right) d\Omega \\ &- s \iint_{\Omega_1} \left(R + q - D\right) f_D\left(D\right) f_R\left(R\right) d\Omega. \end{aligned} \quad (10)$$

To find optimal decision q, it is necessary to calculate the first-order derivative and the second-order derivative of the expected profit. Specifically,

$$\begin{aligned} \frac{dE\left(\Pi_1\right)}{dq} &= p \int_0^{+\infty} \overline{F_D\left(R + q\right)} f_R\left(R\right) dR - c_s \\ &- s \int_0^{+\infty} F_D\left(R + q\right) f_R\left(R\right) dR \\ &= \left(p - c_s\right) \\ &- \left(p + s\right) \int_0^{+\infty} F_D\left(R + q\right) f_R\left(R\right) dR, \\ \frac{d^2 E\left(\Pi_1\right)}{dq^2} &= -\left(p + s\right) \int_0^{+\infty} f_D\left(R + q\right) f_R\left(R\right) dR < 0. \end{aligned} \quad (11)$$

In this formula, $\overline{F(x)} = \int_x^{+\infty} f(x)dx$.

Obviously, expected profit $E(\Pi_1)$ meets the concave function requirement for q. Thus, the maximum point of $E(\Pi_1)$ can be acquired by $dE(\Pi_1)/dq = 0$. Therefore, we have the following.

Proposition 1. *Optimal purchase quantity q of the conventional parts based on structural innovation in the case of part substitution is determined by the following formula:*

$$\int_0^{+\infty} F_D\left(R + q\right) f_R\left(R\right) dR = \frac{p - c_s}{p + s}. \quad (12)$$

3.2. Optimal Decision for Part Complementarity Based on Improved Innovation. The profit function can be expressed as

$$\Pi_2 = \begin{cases} pD - c_c Q - c_r R - s\left(R - D\right), & (R, D) \in \Omega_1, \\ pD - c_c Q - c_r R - s\left(Q - D\right), & (R, D) \in \Omega_2, \\ pQ - c_c Q - c_r R, & (R, D) \in \Omega_3, \\ pR - c_c Q - c_r R, & (R, D) \in \Omega_4. \end{cases} \quad (13)$$

Thus, expected profit $E(\Pi_2)$ is

$$\begin{aligned} E\left(\Pi_2\right) &= \iint_{\Omega_1 \cup \Omega_2 \cup \Omega_3 \cup \Omega_4} \Pi_2 f_D\left(D\right) f_R\left(R\right) d\Omega \\ &= \iint_{\Omega_1} \left[pD - c_c Q - c_r R - s\left(R - D\right)\right] f_D\left(D\right) \\ &\cdot f_R\left(R\right) d\Omega \\ &+ \iint_{\Omega_2} \left[pD - c_c Q - c_r R - s\left(Q - D\right)\right] f_D\left(D\right) \\ &\cdot f_R\left(R\right) d\Omega + \iint_{\Omega_3} \left[pQ - c_c Q - c_r R\right] f_D\left(D\right) \\ &\cdot f_R\left(R\right) d\Omega + \iint_{\Omega_4} \left[pR - c_c Q - c_r R\right] f_D\left(D\right) \\ &\cdot f_R\left(R\right) d\Omega. \end{aligned} \quad (14)$$

So, we can get

$$\begin{aligned} E\left(\Pi_2\right) &= p \iint_{\Omega_1 \cup \Omega_2} D f_D\left(D\right) f_R\left(R\right) d\Omega \\ &+ p \iint_{\Omega_3} Q f_D\left(D\right) f_R\left(R\right) d\Omega \\ &+ p \iint_{\Omega_4} R f_D\left(D\right) f_R\left(R\right) d\Omega - c_c Q \\ &- c_r \iint_{\Omega_1 \cup \Omega_2 \cup \Omega_3 \cup \Omega_4} R f_D\left(D\right) f_R\left(R\right) d\Omega \\ &- s \iint_{\Omega_1} \left(R - D\right) f_D\left(D\right) f_R\left(R\right) d\Omega \\ &- s \iint_{\Omega_2} \left(Q - D\right) f_D\left(D\right) f_R\left(R\right) d\Omega. \end{aligned} \quad (15)$$

To find optimal decision Q, it is necessary to calculate the first-order derivative and the second-order derivative of expected profit $E(\Pi_2)$. Specifically,

$$\begin{aligned}\frac{dE(\Pi_2)}{dq} &= p\overline{F_D(Q)F_R(Q)} - c_c - sF_D(Q)\overline{F_R(Q)},\\ \frac{d^2E(\Pi_2)}{dq^2} &= -(p+s)f_D(Q)\overline{F_R(Q)}\\ &\quad -(p-(p+s)F_D(Q))f_R(Q).\end{aligned} \tag{16}$$

After the calculation, the root of $dE(\Pi_2)/dQ = 0$ is Q^*, which satisfies the equation of $F_D(Q^*) = (p\overline{F_R(Q^*)} - c_c)/(p+s)\overline{F_R(Q^*)}$. Thus,

$$(p+s)F_D(Q^*) = \frac{p\overline{F_R(Q^*)} - c_c}{\overline{F_R(Q^*)}} = p - \frac{c_c}{\overline{F_R(Q^*)}} < p. \tag{17}$$

Accordingly, if $(dE(\Pi_2)/dQ)|_{Q=Q^*} = 0$, then $(d^2E(\Pi_2)/dQ^2)|_{Q=Q^*} < 0$. So, Q^* can maximize expected profit $E(\Pi_2)$.

Proposition 2. *The optimal purchase quantity Q of the conventional parts based on improved innovation in the case of part complementarity is determined by the following formula:*

$$p\overline{F_D(Q)F_R(Q)} - c_c - sF_D(Q)\overline{F_R(Q)} = 0. \tag{18}$$

3.3. Optimal Decision for the Integrated Model with Substitution and Complementarity Based on Improved Innovation. The profit function can be expressed as

$$\Pi_3 = \begin{cases} pD - c_cQ - c_sq - c_rR - s(R+q-D), & (R,D)\in\Omega_1,\\ pD - c_cQ - c_sq - c_rR - s(Q-D), & (R,D)\in\Omega_2,\\ pQ - c_cQ - c_sq - c_rR, & (R,D)\in\Omega_3,\\ p(R+q) - c_cQ - c_sq - c_rR, & (R,D)\in\Omega_4.\end{cases} \tag{19}$$

Thus, the expected profit $E(\Pi_3)$ is

$$\begin{aligned}E(\Pi_3) &= \iint_{\Omega_1\cup\Omega_2\cup\Omega_3\cup\Omega_4}\Pi_3 f_D(D)f_R(R)\,d\Omega\\ &= \iint_{\Omega_1}[pD - c_cQ - c_sq - s(R+q-D)]f_D(D)\\ &\quad\cdot f_R(R)\,d\Omega\\ &\quad + \iint_{\Omega_2}[pD - c_cQ - c_sq - c_rR - s(Q-D)]f_D(D)\\ &\quad\cdot f_R(R)\,d\Omega + \iint_{\Omega_3}[pQ - c_cQ - c_sq - c_rR]\\ &\quad\cdot f_D(D)f_R(R)\,d\Omega\\ &\quad + \iint_{\Omega_4}[p(R+q) - c_cQ - c_sq - c_rR]f_D(D)\\ &\quad\cdot f_R(R)\,d\Omega.\end{aligned} \tag{20}$$

So, we can get

$$\begin{aligned}E(\Pi_3) &= p\iint_{\Omega_1\cup\Omega_2} Df_D(D)f_R(R)\,d\Omega\\ &\quad + p\iint_{\Omega_3} Qf_D(D)f_R(R)\,d\Omega\\ &\quad + p\iint_{\Omega_4}(R+q)f_D(D)f_R(R)\,d\Omega - c_cQ\\ &\quad - c_sq - c_r\iint_{\Omega_1\cup\Omega_2\cup\Omega_3\cup\Omega_4} Rf_D(D)f_R(R)\,d\Omega\\ &\quad - s\iint_{\Omega_1}(R+q-D)f_D(D)f_R(R)\,d\Omega\\ &\quad - s\iint_{\Omega_2}(Q-D)f_D(D)f_R(R)\,d\Omega.\end{aligned} \tag{21}$$

To find optimal decisions Q and q, it is necessary to calculate the first-order derivative and the second-order derivative of expected profit $E(\Pi_3)$. Specifically,

$$\begin{aligned}\frac{\partial E(\Pi_3)}{\partial Q} &= p\overline{F_D(Q)F_R(Q-q)} - c_c - sF_D(Q)\\ &\quad\cdot\overline{F_R(Q-q)},\\ \frac{\partial E(\Pi_3)}{\partial q} &= p\int_0^{Q-q}\overline{F_D(Q)F_R(Q-q)}f_R(R)\,dR - c_s\\ &\quad - s\int_0^{Q-q}F_D(R+q)f_R(R)\,dR,\\ \frac{\partial^2E(\Pi_3)}{\partial Q^2} &= -(p+s)f_D(Q)\overline{F_R(Q-q)} - (p\\ &\quad -(p+s)F_D(Q))f_R(Q-q),\\ \frac{\partial^2E(\Pi_3)}{\partial q^2} &= -p\overline{F_D(Q)}f_R(Q-q)\\ &\quad - p\int_0^{Q-q}f_D(R+q)f_R(R)\,dR\\ &\quad - s\left[-F_D(Q)f_R(Q-q)\right.\\ &\quad \left.+\int_0^{Q-q}f_D(R+q)f_R(R)\,dR\right],\\ \frac{\partial^2E(\Pi_3)}{\partial Q\partial q} &= \frac{\partial^2E(\Pi_3)}{\partial q\partial Q} = -p\overline{F_D(Q)}f_R(Q-q)\\ &\quad - sF_D(Q)f_R(Q-q).\end{aligned} \tag{22}$$

If Q^* and q^* satisfy the equations of $\partial E(\Pi_3)/\partial Q = 0$ and $\partial E(\Pi_3)/\partial q = 0$, then

$$F_D(Q^*) = \frac{p\overline{F_R(Q^* - q^*)} - c_c}{(p+s)\overline{F_R(Q^* - q^*)}},$$
$$p\overline{F_R(Q^* - q^*)} - c_s - (p+s)\int_0^{Q^*-q^*} F_D(R+q^*)\, f_R(R)\, dR = 0. \quad (23)$$

It can be verified that $(\partial^2 E(\Pi_2)/\partial Q^2)|_{\substack{Q=Q^*\\q=q^*}} < 0$, $(\partial^2 E(\Pi_2)/\partial q^2)|_{\substack{Q=Q^*\\q=q^*}} < 0$, $(\partial^2 E(\Pi_2)/\partial Q\partial q)|_{\substack{Q=Q^*\\q=q^*}} > 0$, and

$$\left[\frac{\partial^2 E(\Pi_2)}{\partial Q^2}\frac{\partial^2 E(\Pi_2)}{\partial q^2} - \left(\frac{\partial^2 E(\Pi_2)}{\partial Q\partial q}\right)^2\right]\Bigg|_{\substack{Q=Q^*\\q=q^*}} > 0. \quad (24)$$

So, Q^* and q^* can maximize expected profit $E(\Pi_3)$. Therefore, we have the following.

Proposition 3. *Optimal purchase quantities Q^* and q^* of the substitute and the complementary conventional parts, based on improved innovation in the case of integrated substitution and complementarity, are determined by the following formula:*

$$F_D(Q^*) = \frac{p\overline{F_R(Q^* - q^*)} - c_c}{(p+s)\overline{F_R(Q^* - q^*)}},$$
$$p\overline{F_R(Q^* - q^*)} - c_s - (p+s)\int_0^{Q^*-q^*} F_D(R+q^*)\, f_R(R)\, dR = 0. \quad (25)$$

4. Numerical Analysis

4.1. Numerical Simulation of Part Substitution Based on Structural Innovation. The influence that part recovery uncertainty has on the optimal solution can be studied by setting the values of some parameters. According to [50], $p = 10$, $g = 8$, $s = 2$, $C_c = 3$, $C_r = 2$, $D \sim N(90, 15)$. Here, production depends on recycled parts and conventional new parts. Accordingly, this paper sets R to accord with normal distribution, the mean value as μ, and the variance as σ^2 and takes $\mu = 50$ into account. To observe the influence of the range of numerical values in σ^2 on the optimal strategy and profit, this paper adjusts variance σ^2. The results are shown in Table 1.

From Table 1, for the certain value of μ, the optimal purchase quantity of the substitute conventional parts based on improved innovation will increase. However, the expected profits of the innovative products will decrease, as the variance of recycled quantity R increases.

4.2. Numerical Simulation of Part Complementarity Based on Improved Innovation. Producing innovative products relies entirely on recycled parts. However, in the actual production, the enterprises keep the production scale of the recycled parts close to the demand scale. Here, this paper sets R to accord with the normal distribution, the mean value as μ, and the variance as σ^2 and takes $\mu = 90$ into account. To observe the influence of the range of numeric values in μ and σ^2 on the optimal strategy and profit, this paper adjusts mean value μ and variance σ^2. Table 2 shows the results.

Table 1: Optimal strategy and profit by recovered quantity: part substitution.

Variance	The quantity of substitution parts q	Profit
6	40.44	656.34
8	40.46	655.24
10	40.48	654.19
12	40.50	653.18
14	40.52	652.20
16	40.54	651.26
18	40.55	650.35
20	40.57	649.46

Table 2 shows that, for certain μ values, the optimal purchase quantity of the complementary conventional parts based on improved innovation will increase. However, the expected profits for the innovative products will decrease as recycled quantity R increases. Table 2 also shows that, for certain σ^2 values, the optimal purchase quantity of the complementary conventional parts based on improved innovation will increase as μ value increases. When μ value is close to average D value, then the expected profit will reach its maximum.

This means that if the expected supply quantity is a certain value, with the supply risk increasing, then the effective output will decrease and will need to be compensated by increasing the purchasing quantity. The profits of the innovation products will decrease as the uncertainty increases. Additionally, if the supply risk of the recycled parts is certain, when the expected supply quantity increases, the optimal purchase quantity of the complementary conventional parts will increase. When the expected supply quantity of the recycled parts is close to the expected demand quantity, the expected profits of the innovative products can reach the maximum.

4.3. Numerical Simulation under Integrated Substitution and Complementarity Based on Improved Innovation. Parts can be obtained by substitution or by complementarity when producing products based on improved innovation. If $c_s = 3$ and R accords with the normal distribution, then the mean value is $\mu = 50$ and the variance is σ^2. The other parameters are the same as those in Section 4.2. To observe the influence of σ^2 values on the optimal strategy and profit, this paper adjusts variance σ^2. Table 3 shows the results.

From Table 3, if $\mu = 50$, then the optimal purchase quantity of both the substitute and the complementary parts will increase. However, the expected profits of the innovative products will decrease as the variance of R increases. This

Table 2: Optimal strategy and profit by recovered quantity: part complementarity.

Variance σ^2	$\mu = 80$		$\mu = 90$		$\mu = 100$	
	Quantity demanded Q	Expected profits	Quantity demanded Q	Expected profits	Quantity demanded Q	Expected profits
6	100.00	239.69	104.00	280.23	113.50	215.69
8	100.00	239.58	105.46	273.27	116.00	205.58
10	100.00	239.45	107.00	266.07	118.50	195.45
12	100.00	239.30	109.00	257.05	118.50	195.30
14	100.00	239.14	110.00	252.07	121.00	185.14
16	102.00	230.96	112.00	243.12	122.25	179.96
18	103.00	226.76	113.00	238.21	128.50	154.76
20	104.00	222.56	114.00	233.32	128.50	154.56

Table 3: Optimal strategy and profit by recovered quantity: integrated substitution and complementarity.

Variance	Quantity of substitute part q	Quantity of complementary part Q	Profit
6	38.41	87.66	297.32
8	38.61	87.71	296.11
10	38.79	87.74	295.03
12	38.95	87.77	294.04
14	39.09	87.80	293.13
16	39.23	87.82	292.28
18	39.36	87.84	291.48
20	39.48	87.86	290.72

shows that, to ensure a sufficient output, the purchase quantity of conventional parts will increase, but the expected profits of the innovative products will decrease, as the supply risk of the recycled parts increases. Through the above analysis, an increased fluctuation in the quantity of recycled parts means that the enterprises need gradually decreasing quantities of conventional parts, and the profits for the innovative products also decrease. Analyzing the results shows that an increased fluctuation in R has a greater impact on the optimal purchase quantity of the substitute conventional parts than that of the complementary parts.

5. Conclusion

This paper studies the optimal output decision for innovative products when the quantity of the recycled parts is uncertain. The model aims to maximize the expected profits for innovative products, accounting for both recycled parts and conventional parts. The model analyzes the optimal decision strategy when the recycled parts and the conventional parts are in a substitute relationship and a complementary relationship, namely, under the circumstances of structural innovation and improved innovation. This paper gives the analytic expressions to meet the optimal production quantity and analyzes the relationship between the optimal production quantity and various parameters. When an enterprise produces innovative products—whether based on structural innovation or improved innovation—as the variance of the quantity of the recycled parts increases, the optimal purchase quantity of the conventional parts will increase but the expected profits of the innovative products will decrease. For integrated substitution and complementarity circumstances in cases of improved innovation, fluctuations in the number of recycled parts have a greater impact on the optimal purchase quantity of the substitute conventional parts than that of the complementary parts. In reality, using recycled parts will effectively reduce costs when enterprises produce innovative products. However, fluctuations in the number of available recycled parts will have an impact on the procurement of other parts. When enterprises make decisions about producing innovative products, they should consider the influence of uncertainties in the supply of recycled parts on the expected profits of the innovative products. This study has some shortcomings. The study only discusses the optimal decision in a single period. A multiperiod analysis would more accurately reflect the reality and should be the subject of a further study.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Bilevel Fuzzy Chance Constrained Hospital Outpatient Appointment Scheduling Model

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Hospital outpatient departments operate by selling fixed period appointments for different treatments. The challenge being faced is to improve profit by determining the mix of full time and part time doctors and allocating appointments (which involves scheduling a combination of doctors, patients, and treatments to a time period in a department) optimally. In this paper, a bilevel fuzzy chance constrained model is developed to solve the hospital outpatient appointment scheduling problem based on revenue management. In the model, the hospital, the leader in the hierarchy, decides the mix of the hired full time and part time doctors to maximize the total profit; each department, the follower in the hierarchy, makes the decision of the appointment scheduling to maximize its own profit while simultaneously minimizing surplus capacity. Doctor wage and demand are considered as fuzzy variables to better describe the real-life situation. Then we use chance operator to handle the model with fuzzy parameters and equivalently transform the appointment scheduling model into a crisp model. Moreover, interactive algorithm based on satisfaction is employed to convert the bilevel programming into a single level programming, in order to make it solvable. Finally, the numerical experiments were executed to demonstrate the efficiency and effectiveness of the proposed approaches.

1. Introduction

In recent years, due to reasons such as the increase in population and intensification of the aging problem, the number of patients has increased rapidly. The phenomenon of "out of capacity" has appeared in many large hospitals; patients often wait in line overnight, even paying high prices to ticket vendors in order to register for a patient number in the hospitals. At the same time, the highly specialized nature of the hospital determined that a hospital resource cannot be shared by multiple people simultaneously, and leaving the resource unused will not produce any benefits. Therefore, hospitals are facing the problem of how to increase the profit with limited resources. Treating the patients is the core service of a hospital and also is the biggest source of income. Since the first part of the treatment process is appointment scheduling, therefore, a hospital's appointment scheduling status directly decides its treatment possibility and efficiency. Thus, it is necessary to optimize the daily number of treatments and maximize the bearing capacity of doctors to meet the treatment needs of patients and combine revenue and hospital management in order to improve the overall efficiency of hospitals.

The main issue related to appointment scheduling is balancing the treatment needs of patients and the bearing capacity of doctors. The demand for treatment is often greater than the supply, causing patients unable to receive the treatment on time and reducing the quality of life of patients. As Cayirli points out at the Program, Decision Science Institute Conference, the traditional medical

scheduling problem aims to improve resource utilization and reduce the wait time [1]. Bailey used the queuing theory to study the appointment scheduling system of hospitals [2]. Lindley discussed the opportunities and challenges of the application of appointment scheduling in hospital resources such as outpatient departments and operating rooms [3], proposed the characteristics that hospitals need to treat patients quickly and use doctors efficiently, and suggested dividing the working time of doctors into multiple periods; appointment scheduling staff can determine the number of doctors during these periods according to the patient demand and reserve a certain amount of time for emergency patients through inventory control.

Riise et al. pointed out that the overall cost effectiveness and treatment efficiency were becoming increasingly important for outpatient scheduling, and they built an integer linear program model with variable resource availability and resource setup times [4]. Samorani and LaGanga combined predictive analytics, optimization, and overbooking to maximize the number of treated patients while minimizing waiting time and overtime [5]. Jebali et al. used a two-stage method to deal with the preschedule and distribution scheduling problem; the author proposed a 0-1 linear programming model to minimize problems such as the time cost for patients waiting for surgery and the hospitalization cost [6]. Most of the research based on the queuing theory is a single queue of steady state behavior with the same customers and arrival time. However, as Bailey points out, since it involves only a limited number of patients, not reaching the steady state, therefore, the results of steady state queuing are usually not suitable for the appointment scheduling system [7]. Vanden Bosch and Dietz considered the possibility of failure to make the appointment during appointment scheduling [8].

It has been found that the former approaches mostly take a certain outpatient department as the research object; all the decision variables were controlled by it. However, in the realistic decision system of the hospital outpatient appointment scheduling, there are two kinds of decision makers: hospital and outpatient departments. They make different decisions: the hospital usually owns the power to promote or demote doctors, and the departments can arrange the appointment scheduling. Unfortunately, the existing models are mostly weak to deal with such hierarchy decision system. Therefore, this is a need to develop a bilevel programming to describe and solve the hospital outpatient appointment scheduling problem with multiple decision making participants.

In healthcare, it is common that hospitals do not receive payments from the patients directly. The payments usually come from government or commercial companies. Different sources of payment may lead to varying revenue. Therefore, the classification based on the insurances of patients should be worth noting. Customers in hospital outpatient departments can be divided into different classes based on their payment source and revenue contribution. The following three classes are to be considered: customer with Medicare (Medicare is run by the government and can cover a portion of medical charges); customer with Medicaid (Medicaid is a joint program run by both province and government and other organizations); customer with commercial insurances. So this paper intends to introduce patient classification to hospital outpatient scheduling problem and apply revenue management to deal with it.

Revenue management works best when there is a limited available capacity and when the customers are ready to pay different amount for the same service. It is mainly used in airlines, hotel, and other industries; these industries have one common characteristic: they need to sell the products in a certain period time; otherwise, the products will lose their value once the time period passes. Therefore, Lieberman proposed the application of revenue management in the health care industry [9]. Gupta and Wang also clearly suggested the application of revenue management in the hospital outpatient appointment scheduling management [10]. As an important part of revenue management, capacity distribution determines the number of appointments available according to the product price in order to meet the needs of all consumers. This theory was first proposed to solve the problem of duo-price level in the aircraft. Gosavi et al. and Hamzaee and Vasigh proposed the problem of seat allocation and defined different prices of selling seats for different customers [11, 12]. Although the study of revenue management has entered the health care industry and has achieved some results [13, 14], however, most of the research is concentrated in surgery scheduling [15–17]. Therefore, the research on the revenue management in hospitals is still insufficient.

In summary, the paper takes the appointment scheduling of the outpatient department as the research subject, based on the uncertainty of the health care industry, comprehensively considers the objectives such as maximizing the hospital income and minimizing the department capacity surplus, and establishes the bilevel optimization model under the fuzzy environment in order to achieve appropriate scheduling and income satisfaction simultaneously. The potential contribution lies in the following: (i) Most of the previous papers about healthcare management consider appointment scheduling and revenue management separately. This paper combines the two aspects and considers them comprehensively in order to establish an appointment scheduling model based on revenue management. (ii) This paper will employ fuzzy variables as the tool and effectively describes the uncertainties in the healthcare industry caused by inaccurate data measurement and information loss during transfer, and so forth. (iii) This paper aims at the bilevel decision problem of hospital and departments, establishes a bilevel appointment scheduling optimization model under the fuzzy environment, and helps hospitals to achieve appropriate scheduling and income satisfaction simultaneously.

The structure of this paper is organized in five sections. In Section 2, we describe the key features of the hospital outpatient appointment scheduling. In Section 3, the mathematical formulation is developed, and the equivalent transformation is also presented. An interactive method based on the satisfactory solution is proposed in Section 4. Case study is presented in Section 5. Finally, the conclusions are provided in Section 6.

2. Problem Statement

How to arrange the appointment scheduling policy according to the characteristics of the healthcare industry is a key problem for hospitals. This part considers the hospital management section as the top decision maker who mainly determines the hiring number of doctors and hospital departments as lower level decision makers who mainly conduct appointment scheduling for their own departments. It establishes a bilevel multiobjective optimization model. However, due to some reasons, the data collection of the healthcare industry is insufficient; therefore, the model contains uncertain parameters that are processed through chance constraints.

2.1. Motivation for Employing Fuzzy Variables. A fuzzy set is often used to describe an ambiguous event or object. A patient's treatment process, from the initial treatment to the end, will be accompanied by a variety of uncertainties. Since it is difficult to accurately collect the data related to these uncertainties, we usually use a rough estimate from experts in the field, which is using the fuzzy membership function to describe similar uncertainties.

In the hospital outpatient appointment scheduling problem, the uncertainty factors come from four main aspects: the doctor bearing capacity, the doctor wage, patient demand, and hospital income. Firstly, since the size of the doctor's bearing capacity is affected by many factors such as the doctor's experience and the complexity of the patient's condition, it cannot be accurately determined. Secondly, the difference in title, years of experience, and departments of doctors will lead to difference in doctor wage. Thirdly, the uncertainty of the patient's needs is mainly manifested in the patient's subjective judgment of the hospital's abilities and the need for medical treatment, as well as the expectation of the treatment cost and individual's preference, and so forth. Finally, due to the uncertainty of factors above, the hospital income also shows uncertainty. Therefore, when considering the doctor's bearing capacity and wages, this paper conducts sampling analysis with the aid of historical data and uses the estimates of the experts in the industry, ultimately forming a fuzzy variable. Usually, methods forecasting demands have certain models or assumptions, assuming that the demand operates according to certain rules or shows a certain pattern. However, any prediction method has some defects that cannot accurately predict the fluctuation in demand and the psychological reaction of consumers. Based on the above four aspects of uncertainty, this paper uses fuzzy number to replace the concrete data to get the results closest to the real-life situation.

2.2. Motivation for Using Bilevel Programming. The constraint conditions of the bilevel programming model include one or more programming models and the differences that exist between objective functions. For the healthcare industry, the hospital management section and every department play an important role in their respective obligations; the size and position of their respective goals are also different. As upper level decision maker, hospital management level will consider maximizing the total economic benefits; as lower level decision makers, the hospital departments often take their own economic benefit as the primary goal. However, due to the limitations of medical funds, the department has to consider the cost of human resources and minimize the capacity surplus. Taking into account the above factors, the above problem should be considered as a bilevel optimization problem, where the upper level decision makers are the hospital management and the lower level decision makers are the hospital departments. Information between the two levels of decision makers is exchangeable. Therefore, the goals and the constraints of both levels are understandable by each other. In summary, this paper constructs the model and applies it to the entire hospital outpatient appointment scheduling based on the combination of uncertainty theory and bilevel programming.

This paper has the following assumptions:

(1) The hospital is divided into multiple departments. The total income of the hospital is the sum of all incomes from all departments.

(2) The working time of doctors is divided into multiple time slots, and the patient needs to schedule an appointment prior to treatment and receives the treatment in the corresponding time.

(3) Doctors are divided into full time and part time physicians.

(4) The doctor's wages are divided into basic salary and the merit pay according to the number of treatments.

(5) All departments fully corporate and implement the policy of the hospital. The information between hospital and departments is fully interchangeable.

3. Modeling

In what follows, we propose a bilevel programming model with fuzzy coefficients to solve the appointment scheduling problem based on the hospital revenue management. Three different customer classes, customers with Medicare, customers with Medicaid, and customers with commercial insurance, are considered in developing mathematical models for appointment scheduling in hospital outpatient departments.

3.1. Notation. The following symbols are used in the appointment scheduling model:

(1) Indices

m: department, in which $m = 1, 2, \ldots, M$

i: insurance, in which $i = 1, 2, \ldots, I$

a^m: appointment time slot in department m, in which $a^m = 1, 2, \ldots, A^m$

t^m: treatment in department m, in which $t^m = 1, 2, \ldots, T^m$

d^m: doctor in department m, in which $d^m = 1, 2, \ldots, D^m$.

(2) Parameters

$\widetilde{\text{Sal}}_{md^m}$: daily basic salary of d doctor in department m

$\widetilde{R}_{mt^mi}$: the income hospital receives from patient with insurance i performed treatment t^m in department m

$\widetilde{C}_{mt^md^m}$: merit pay of d doctor of department m performing treatment t^m once

Cap_{md^m}: daily bearing capacity of d doctor in department m

$\widetilde{\text{Dem}}_{mt^m}$: demand for treatment t^m in department m every day

$\widetilde{\text{Demins}}_{mt^mi}$: demand for treatment t^m using insurance i in department m every day

$$Z_{md^mt^m} = \begin{cases} 1, & \text{If doctor } d^m \text{ of department } m \text{ can be assigned for treatment } t^m \\ 0, & \text{Otherwise.} \end{cases} \tag{1}$$

(3) Decision Variables

$$X_{md^ma^mt^mi} = \begin{cases} 1, & \text{If doctor } d^m \text{ of department } m \text{ performs treatment } t^m \text{ to patient with insurance } i \text{ in time slot } a^m \\ 0, & \text{Otherwise} \end{cases} \tag{2}$$

$$Y_{md^m} = \begin{cases} 1, & \text{If doctor } d^m \text{ of department } m \text{ is selected} \\ 0, & \text{Otherwise} \end{cases}$$

3.2. Upper Level Model. As the upper level decision maker, the hospital management section takes the total hospital profit as the primary goal. Since the hospital treatment is divided by departments, therefore, this model first calculates the income of every department and then sums up the income of every department to obtain the overall income of the hospital. Equation (3) is composed of doctor's income and expenditure.

$$\begin{aligned} \max \quad F_1 &= \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\widetilde{R}_{mt^mi} - \widetilde{C}_{mt^md^m}\right) X_{md^ma^mt^mi} \\ &\quad - \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \widetilde{\text{Sal}}_{md^m} Y_{md^m}. \end{aligned} \tag{3}$$

Constraint Conditions: Number of Doctors' Constraint. The number of doctors cannot exceed the number of available doctors:

$$\sum_{d^m=1}^{D^m} Y_{md^m} \le D^m, \quad \forall m \in M. \tag{4}$$

Equation (5) ensures that a patient can be scheduled for an appointment with a doctor only if that doctor is selected:

$$\begin{aligned} &X_{md^ma^mt^mi} \le Y_{md^m}, \\ &\forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I. \end{aligned} \tag{5}$$

3.3. Lower Level Model. As the lower level decision maker, every department will schedule appointments for patients according to the actual situation. Objective function: the hospital department takes its own profit as the primary goal while minimizing the gap between the capacity and demand. Equation (6) is composed of doctor's income and expenditure exhibits the object of maximizing the profit of the department:

$$\begin{aligned} \max \quad f_m^1 &= \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\widetilde{R}_{mt^mi} - \widetilde{C}_{mt^md^m}\right) X_{md^ma^mt^mi} \\ &\quad - \sum_{d^m=1}^{D^m} \widetilde{\text{Sal}}_{md^m} Y_{md^m}, \quad \forall m \in M. \end{aligned} \tag{6}$$

Equation (7) shows the department needs to balance capacity and demand to minimize surplus capacity:

$$\begin{aligned} \min \quad f_m^2 &= \sum_{d^m=1}^{D^m} \text{Cap}_{md^m} Y_{md^m} \\ &\quad - \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i}^{I} X_{md^ma^mt^mi}, \quad \forall m \in M. \end{aligned} \tag{7}$$

Constraints are as follows.

Ability Constraint. The number of patients treated in any group cannot exceed a doctor's ability:

$$\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le \mathrm{Cap}_{md^m}, \quad \forall m \in M,\ d^m \in D^m. \tag{8}$$

Demand Constraint. The number of treatments for any disease cannot exceed the total number of patients who need to have medical treatment:

$$\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le \widetilde{\mathrm{Dem}}_{mt^m}, \quad \forall m \in M,\ t^m \in T^m. \tag{9}$$

Equation (10) ensures that the total number of patients seen that belong to one of the insurance sources does not exceed the demand for that particular insurance:

$$\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}X_{md^ma^mt^mi} \le \widetilde{\mathrm{Demins}}_{mt^mi}, \quad \forall m \in M,\ t^m \in T^m,\ i \in I. \tag{10}$$

Equation (11) ensures that a treatment is assigned to a doctor, only the doctor who is skilled to handle the treatment:

$$X_{md^ma^mt^mi} \le Z_{md^mt^m}, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I. \tag{11}$$

Equation (12) ensures that doctor treats one patient per treatment:

$$\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le 1, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m. \tag{12}$$

From above, we obtain the entire model:

$$\begin{aligned}
&\max \quad F_1 = \sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\widetilde{R}_{mt^mi} - \widetilde{C}_{mt^md^m}\right)X_{md^ma^mt^mi} - \sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\widetilde{\mathrm{Sal}}_{md^m}Y_{md^m} \\
&\text{s.t.} \quad \begin{cases}
\displaystyle\sum_{d^m=1}^{D^m}Y_{md^m} \le D^m, \quad \forall m \in M \\
X_{md^ma^mt^mi} \le Y_{md^m}, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I \\
\begin{cases}
\max \quad f_m^1 = \displaystyle\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\widetilde{R}_{mt^mi} - \widetilde{C}_{mt^md^m}\right)X_{md^ma^mt^mi} - \displaystyle\sum_{d^m=1}^{D^m}\widetilde{\mathrm{Sal}}_{md^m}Y_{md^m}, \quad \forall m \in M \\
\min \quad f_m^2 = \displaystyle\sum_{d^m=1}^{D^m}\mathrm{Cap}_{md^m}Y_{md^m} - \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i}^{I}X_{md^ma^mt^mi}, \quad \forall m \in M \\
\text{s.t.} \quad \begin{cases}
\displaystyle\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le \mathrm{Cap}_{md^m}, \quad \forall m \in M,\ d^m \in D^m \\
\displaystyle\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le \widetilde{\mathrm{Dem}}_{mt^m}, \quad \forall m \in M,\ t^m \in T^m \\
\displaystyle\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}X_{md^ma^mt^mi} \le \widetilde{\mathrm{Demins}}_{mt^mi}, \quad \forall m \in M,\ t^m \in T^m,\ i \in I \\
X_{md^ma^mt^mi} \le Z_{md^mt^m}, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I \\
\displaystyle\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}X_{md^ma^mt^mi} \le 1, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m.
\end{cases}
\end{cases}
\end{cases}
\end{aligned} \tag{13}$$

3.4. Bilevel Chance Constrained Appointment Scheduling Model. Since model (13) contains fuzzy parameters $\widetilde{\mathrm{Sal}}_{md^m}$, $\widetilde{R}_{mt^mi}$, $\widetilde{C}_{mt^md^m}$, $\widetilde{\mathrm{Dem}}_{mt^m}$, and $\widetilde{\mathrm{Demins}}_{mt^mi}$ therefore, model (13) is not a real mathematical model under the definition. It

needs to be further processed and transformed into a solvable model with mathematical meaning. In the following, model (13) is transformed as described below.

3.4.1. Model Processing. For upper level decision makers, since there exists fuzzy parameters in objective function (3), therefore, it is difficult for decision makers to accurately determine the maximum profit. Thus, the upper level decision makers attempt to consider the risks and hope to maximize the profit under a certain confidence level (possibility); that is, (3) can be transformed into

$$\begin{aligned} &\max \quad \overline{F}_1 \\ &\text{s.t.} \quad \operatorname{Pos}\left\{\sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\widetilde{R}_{mt^mi}-\widetilde{C}_{mt^md^m}\right)X_{md^ma^mt^mi}-\sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\widetilde{\mathrm{Sal}}_{md^m}Y_{md^m}\geq\overline{F}_1\right\}\geq\gamma_1. \end{aligned} \tag{14}$$

For the lower level decision makers, since there exist fuzzy parameters in objective function (6), therefore, it is difficult for decision makers to accurately determine the maximum profit. Thus, the lower level decision makers attempt to consider the risks and hope to maximize profit under a certain confidence level (possibility). Based on this, we can transform objective function (6) into objective function (15) with chance constraint

$$\begin{aligned} &\max \quad \overline{f}_m^1 \\ &\text{s.t.} \quad \operatorname{Pos}\left\{\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\widetilde{R}_{mt^mi}-\widetilde{C}_{mt^md^m}\right)X_{md^ma^mt^mi}-\sum_{d^m=1}^{D^m}\widetilde{\mathrm{Sal}}_{md^m}Y_{md^m}\geq\overline{f}_m^1\right\}\geq\gamma_2. \end{aligned} \tag{15}$$

Moreover, since there exist fuzzy parameters in constraint conditions (9)-(10), therefore, the decision maker will guarantee the possibility that the number of treatments is no more than the patients' demand being larger than a certain level; thus, (9) and (10) can be transformed into (16) and (17), respectively:

$$\operatorname{Pos}\left\{\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{i=1}^{I}X_{md^ma^mt^mi}\leq\widetilde{\mathrm{Dem}}_{mt^m}\right\}\geq\gamma_5, \tag{16}$$

$$\operatorname{Pos}\left\{\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}X_{md^ma^mt^mi}\leq\widetilde{\mathrm{Demins}}_{mt^mi}\right\}\geq\gamma_6. \tag{17}$$

3.4.2. Model Equivalent Transformation

Lemma 1 (see [18]). *Assume that there exists the following L-R type fuzzy variable below: $\xi_1 = (m_1, \alpha_1, \beta_1)_{LR}$ and $\xi_2 = (m_2, \alpha_2, \beta_2)_{LR}$, where m_1 and m_2 are the median of ξ_1, ξ_2, respectively; α_1, α_2 and β_1, β_2 are the left width and right width of ξ_1, ξ_2, respectively. Then we have*

$$\begin{aligned} \xi_1+\xi_2&=(m_1+m_2,\alpha_1+\alpha_2,\beta_1+\beta_2)_{LR},\\ \xi_1-\xi_2&=(m_1-m_2,\alpha_1+\beta_2,\beta_1+\alpha_2)_{LR},\\ k\xi_1&=(km_1,k\alpha_1,k\beta_1)_{LR},\quad k>0\\ \operatorname{Pos}\{\xi_1\geq\xi_2\}\geq\alpha&\Longleftrightarrow m_{1\alpha}^R\geq m_{2\alpha}^L, \end{aligned} \tag{18}$$

where $m_{1\alpha}^R$ is the right end point of α cut of ξ_1, $m_{2\alpha}^L$ is the left end point of α cut of ξ_2.

Let the model parameters $\widetilde{\mathrm{Sal}}_{md^m}$, $\widetilde{R}_{mi}$, $\widetilde{C}_{md^m}$, $\widetilde{\mathrm{Dem}}_{mt^m}$, and $\widetilde{\mathrm{Demins}}_{mt^mi}$ be triangular fuzzy numbers (a special *L-R* type fuzzy number with the left and the right reference functions $L(x) = R(x) = 1 - x$), shown as follows:

$$\begin{aligned} \widetilde{\mathrm{Sal}}_{md^m}&=\left(\mathrm{Sal}_{md^m},\alpha_{\mathrm{Sal}_{md^m}},\beta_{\mathrm{Sal}_{md^m}}\right)_{LR};\\ \widetilde{R}_{mt^mi}&=\left(R_{mt^mi},\alpha_{R_{mt^mi}},\beta_{R_{mt^mi}}\right)_{LR};\\ \widetilde{C}_{mt^md^m}&=\left(C_{mt^md^m},\alpha_{C_{mt^md^m}},\beta_{C_{mt^md^m}}\right)_{LR};\\ \widetilde{\mathrm{Dem}}_{mt^m}&=\left(\mathrm{Dem}_{mt^m},\alpha_{\mathrm{Dem}_{mt^m}},\beta_{\mathrm{Dem}_{mt^m}}\right)_{LR};\\ \widetilde{\mathrm{Demins}}_{mt^mi}&=\left(\mathrm{Demins}_{mt^mi},\alpha_{\mathrm{Demins}_{mt^mi}},\beta_{\mathrm{Demins}_{mt^mi}}\right)_{LR}. \end{aligned} \tag{19}$$

Then, according to Lemma 1, we can obtain

$$F_1 = \left(\begin{array}{l} \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} - \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \mathrm{Sal}_{md^m} Y_{md^m}, \\ \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\alpha_{R_{mt^m i}} + \beta_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \beta_{\mathrm{Sal}_{md^m}} Y_{md^m}, \\ \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \alpha_{\mathrm{Sal}_{md^m}} Y_{md^m} \end{array} \right)_{LR}. \tag{20}$$

It means that F_1 is also a triangular fuzzy number; the left and right end points of the γ_1 cut set are

$$\begin{aligned} &\sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} \\ &\quad - \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \mathrm{Sal}_{md^m} Y_{md^m} - (1-\gamma_1) \\ &\quad \cdot \left[\sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\alpha_{R_{mt^m i}} + \beta_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} \right. \\ &\quad \left. + \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \beta_{\mathrm{Sal}_{md^m}} Y_{md^m} \right], \end{aligned}$$

$$\begin{aligned} &\sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} \\ &\quad - \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \mathrm{Sal}_{md^m} Y_{md^m} + (1-\gamma_1) \\ &\quad \cdot \left[\sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} \right. \\ &\quad \left. + \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \alpha_{\mathrm{Sal}_{md^m}} Y_{md^m} \right]. \end{aligned} \tag{21}$$

From Lemma 1 we know that (14) can be equivalently transformed into

$$\begin{aligned} \max \quad & \overline{F}_1 \\ \text{s.t.} \quad & \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} - \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \mathrm{Sal}_{md^m} Y_{md^m} \\ & + (1-\gamma_1) \left[\sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{m=1}^{M} \sum_{d^m=1}^{D^m} \alpha_{\mathrm{Sal}_{md^m}} Y_{md^m} \right] \geq \overline{F}_1. \end{aligned} \tag{22}$$

Therefore, from the derivation process of (22), (15)–(17) can be transformed to (23)–(25), respectively:

$$\begin{aligned} \max \quad & \overline{f}_m^1 \\ \text{s.t.} \quad & \sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} - \sum_{d^m=1}^{D^m} \mathrm{Sal}_{md^m} Y_{md^m} \\ & + (1-\gamma_2) \left[\sum_{d^m=1}^{D^m} \sum_{a^m=1}^{A^m} \sum_{t^m=1}^{T^m} \sum_{i=1}^{I} \left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{d^m=1}^{D^m} \alpha_{\mathrm{Sal}_{md^m}} Y_{md^m} \right] \\ & \geq \overline{f}_m^1, \end{aligned} \tag{23}$$

$$\mathrm{Dem}_{mt^m} + (1-\gamma_3)\,\beta_{\mathrm{Dem}_{mt^m}} \geq \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{i=1}^{I} X_{md^m a^m t^m i}, \tag{24}$$

$$\mathrm{Demins}_{mt^m i} + (1-\gamma_4)\,\beta_{\mathrm{Demins}_{mt^m i}} \geq \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m} X_{md^m a^m t^m i}. \tag{25}$$

Concluding the above, there exists an equivalent solvable model:

$$\begin{aligned}
&\max \quad \overline{F}_1\\
&\text{s.t.} \begin{cases}
\sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} - \sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\mathrm{Sal}_{md^m} Y_{md^m}\\
\quad + (1-\gamma_1)\left[\sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{m=1}^{M}\sum_{d^m=1}^{D^m}\alpha_{\mathrm{Sal}_{md^m}} Y_{md^m}\right] \geq \overline{F}_1\\
\sum_{d^m=1}^{D^m} Y_{md^m} \leq D^m, \quad \forall m \in M\\
X_{md^m a^m t^m i} \leq Y_{md^m}, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I\\
\max \quad \overline{f}_m^1\\
\min \quad f_m^2 = \sum_{d^m=1}^{D^m}\mathrm{Cap}_{md^m} Y_{md^m} - \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i}^{I} X_{md^m a^m t^m i}, \quad \forall m \in M\\
\text{s.t.} \begin{cases}
\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(R_{mt^m i} - C_{mt^m d^m}\right) X_{md^m a^m t^m i} - \sum_{d^m=1}^{D^m}\mathrm{Sal}_{md^m} Y_{md^m}\\
\quad + (1-\gamma_2)\left[\sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I}\left(\beta_{R_{mt^m i}} + \alpha_{C_{mt^m d^m}}\right) X_{md^m a^m t^m i} + \sum_{d^m=1}^{D^m}\alpha_{\mathrm{Sal}_{md^m}} Y_{md^m}\right] \geq \overline{f}_m^1\\
\sum_{a^m=1}^{A^m}\sum_{t^m=1}^{T^m}\sum_{i=1}^{I} X_{md^m a^m t^m i} \leq \mathrm{Cap}_{md^m}, \quad \forall m \in M,\ d^m \in D^m\\
\mathrm{Dem}_{mt^m} + (1-\gamma_3)\,\beta_{\mathrm{Dem}_{mt^m}} \geq \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m}\sum_{i=1}^{I} X_{md^m a^m t^m i}, \quad \forall m \in M,\ t^m \in T^m\\
\mathrm{Demins}_{mt^m i} + (1-\gamma_4)\,\beta_{\mathrm{Demins}_{mt^m i}} \geq \sum_{d^m=1}^{D^m}\sum_{a^m=1}^{A^m} X_{md^m a^m t^m i}, \quad \forall m \in M,\ t^m \in T^m,\ i \in I\\
X_{md^m a^m t^m i} \leq Z_{md^m t^m}, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m,\ t^m \in T^m,\ i \in I\\
\sum_{t^m=1}^{T^m}\sum_{i=1}^{I} X_{md^m a^m t^m i} \leq 1, \quad \forall m \in M,\ d^m \in D^m,\ a^m \in A^m.
\end{cases}
\end{cases}
\end{aligned} \tag{26}$$

4. Solution Approach

The bilevel multiobjective programming has always been a difficult NP problem; it is usually solved using Stackelberg solution. However, Stackelberg solution is suitable for the situation where two sides are not cooperating with each other. In the above model, the upper and lower level decision makers have the same interests; thus, there exists a cooperative motive. The upper and lower level decision makers can interact with a certain degree of satisfaction. Therefore, this

paper uses the interactive algorithm based on satisfaction to solve model (26); the detailed steps are as follows.

4.1. Eliciting Satisfactory Degree Functions. Assume (x_0^1, y_0^1), (x_m^1, y_m^1), and (x_m^2, y_m^2) are optimized solutions of objective functions of $\max F_1(x, y)$, $\max f_m^1(x, y)$, and $\min f_m^2(x, y)$, where $m = 1, 2, \ldots, M$. Then the maximum values of the objective functions are

$$F_{1\max}(x, y) = F_1\left(x_0^1, y_0^1\right), \tag{27}$$

$$f_{m\max}^1(x, y) = \max_{m=1,2,\ldots,M} f_m^1\left(x_m^1, y_m^1\right), \tag{28}$$

$$f_{m\max}^2(x, y) = \max_{m=1,2,\ldots,M} \left\{f_m^2\left(x_0^1, y_0^1\right), f_m^2\left(x_m^1, y_m^1\right)\right\}. \tag{29}$$

And the minimum values of the objective functions are

$$F_{1\min}(x, y) = \min_{m=1,2,\ldots,M} \left\{F_1\left(x_m^1, y_m^1\right), F_1\left(x_m^2, y_m^2\right)\right\}, \tag{30}$$

$$f_{m\min}^1(x, y) = \min_{m=1,2,\ldots,M} \left\{f_m^1\left(x_0^1, y_0^1\right), f_m^1\left(x_m^2, y_m^2\right)\right\}, \tag{31}$$

$$f_{m\min}^2(x, y) = \min_{m=1,2,\ldots,M} f_m^2\left(x_m^2, y_m^2\right). \tag{32}$$

Therefore, we construct the following satisfaction functions for the upper level decision maker and every lower level decision maker:

$$\mathrm{SD}_0(F_1(x, y)) = \begin{cases} 1 & F_1(x, y) \geq F_{1\max} \\ \dfrac{F_1(x, y) - F_{1\min}}{F_{1\max} - F_{1\min}} & F_{1\min} < F_1(x, y) \leq F_{1\max} \\ 0 & F_1(x, y) < F_{1\min}, \end{cases}$$

$$\mathrm{SD}_m^1\left(f_m^1(x, y)\right) = \begin{cases} 1 & f_m^1(x, y) \geq f_{m\max}^1 \\ \dfrac{f_m^1(x, y) - f_{m\min}^1}{f_{m\max}^1 - f_{m\min}^1} & f_{m\min}^1 < f_m^1(x, y) \leq f_{m\max}^1 \\ 0 & f_m^1(x, y) < f_{m\min}^1, \end{cases} \tag{33}$$

$$\mathrm{SD}_m^2\left(f_m^2(x, y)\right) = \begin{cases} 1 & f_m^2(x, y) \leq f_{m\min}^2 \\ \dfrac{f_{m\max}^2 - f_m^2(x, y)}{f_{m\max}^2 - f_{m\min}^2} & f_{m\min}^2 < f_m^2(x, y) \leq f_{m\max}^2 \\ 0 & f_m^2(x, y) > f_{m\max}^2, \end{cases}$$

where $F_{1\max}$ and $F_{1\min}$ are the maximum value and minimum value of the upper level objective function, respectively and $f_{m\max}^i$ and $f_{m\min}^i$ $(m = 1, 2, \ldots, M,\ i = 1, 2)$ are the maximum value and minimum value of the lower level objective functions, respectively.

4.2. Evaluating Satisfactory Solution. After determining the upper and lower level of satisfaction functions, each decision maker will first determine the minimum acceptable satisfaction level according to their own circumstances: the upper level decision maker's acceptable satisfaction level is $\lambda_0^1 \in [0, 1]$ and the lower level decision makers' acceptable satisfaction level is λ_m^i, $m = 1, 2, \ldots, M$, $i = 1, 2$.

Then, under the condition of the problem constraint and satisfying the upper decision maker, the lower decision makers can optimize their satisfaction levels, shown in

$$\begin{aligned} &\max \quad \lambda \\ &\text{s.t.} \quad \begin{cases} \mathrm{SD}_0(F_1(x, y)) \geq \lambda_0^1 \\ \mathrm{SD}_m^i\left(f_m^i(x, y)\right) \geq \lambda, \quad m = 1, 2, \ldots, M,\ i = 1, 2 \\ (x, y) \in Q, \end{cases} \end{aligned} \tag{34}$$

where λ is the assistant variable and Q is the feasible region of model (26). Assume that the optimal solution for model (34) is $X = (x^*, y^*, \lambda^*)$.

The minimum satisfaction level of the upper level decision maker is predetermined; then we can use the following way to determine whether $X = (x^*, y^*, \lambda^*)$ is a satisfactory solution of the bilevel model: if $\mathrm{SD}_m^i(f_m^i(x^*, y^*)) \geq \lambda_m^i$ holds for all $m = 1, 2, \ldots, M$, $i = 1, 2$, then it is the solution to the satisfaction level of the lower level; if $\mathrm{SD}_m^i(f_m^i(x, y)) \leq \lambda_m^i$ holds for all $m = 1, 2, \ldots, M$, $i = 1, 2$, then the upper decision level must lower its minimum satisfaction level in order to increase the satisfaction level of the lower level.

If the optimal solution $X = (x^*, y^*, \lambda^*)$ of model (34) satisfies the above conditions, then the solution can be considered as a satisfactory solution to model (26).

5. Numerical Example

The model is tested below, and the test results are analyzed to verify the validity of the proposed model.

5.1. Related Data. Assume a hospital has three departments, A, B and C, and each department can perform one treatment. There are 12 time slots a day, and one appointment can be arranged in each time slot. In other words, one patient will be treated in a slot. Since we divide the patients into three classes based on the insurances they hold, different classes bring different revenue to the hospital, and the detailed data is shown in Table 1. In Table 1, we use I1, I2, and I3 to indicate Medicaid, Medicare, and commercial insurance, respectively.

The hospital should make the payment for the cost of the used doctors, which includes the merit pay and the basic salary. If a doctor is used, the basic salary should be paid. And the merit pay is related to the number of the patients a doctor treated. It is assumed that a full time doctor is paid less than a part time doctor per unit time. Table 2 describes the relevant data.

Table 3 presents the demand for each department. Three scenarios are given: the demand is less than the total capacity, the demand is near the total capacity, and the demand is more than the total capacity.

Table 1: Treatment revenue based on different patients' insurances.

Department	Patient		
	I1	I2	I3
A	(100, 20, 20)	(150, 20, 20)	(200, 20, 20)
B	(150, 30, 30)	(200, 30, 30)	(250, 30, 30)
C	(200, 30, 30)	(250, 30, 30)	(300, 30, 30)

Table 2: Doctors' merit pay and basic salary.

Department	Doctor type	Number	Merit pay	Basic salary
A	Full time	5	(20, 5, 5)	(130, 10, 10)
	Part time	3	(50, 5, 5)	(150, 10, 10)
B	Full time	5	(30, 5, 5)	(150, 10, 10)
	Part time	2	(60, 5, 5)	(170, 10, 10)
C	Full time	3	(40, 5, 5)	(180, 10, 10)
	Part time	1	(70, 5, 5)	(200, 10, 10)

Table 3: Demand under three kinds of scenarios.

Scenario	Department	Demand			Total demand
		I1	I2	I3	
(I) Demand < capacity	A	(20, 2, 2)	(23, 2, 2)	(2, 1, 1)	(45, 5, 5)
	B	(20, 2, 2)	(23, 2, 2)	(2, 1, 1)	(45, 5, 5)
	C	(10, 2, 2)	(10, 2, 2)	(2, 1, 1)	(20, 5, 5)
(II) Demand ≈ capacity	A	(22, 2, 2)	(35, 2, 2)	(3, 1, 1)	(60, 5, 5)
	B	(25, 2, 2)	(30, 2, 2)	(5, 1, 1)	(60, 5, 5)
	C	(15, 2, 2)	(18, 2, 2)	(2, 1, 1)	(35, 5, 5)
(III) Demand > capacity	A	(37, 2, 2)	(52, 2, 2)	(6, 1, 1)	(95, 5, 5)
	B	(33, 2, 2)	(46, 2, 2)	(6, 1, 1)	(85, 5, 5)
	C	(20, 2, 2)	(20, 2, 2)	(5, 1, 1)	(45, 5, 5)
(IV) Demand > capacity	A	(50, 2, 2)	(52, 2, 2)	(8, 1, 1)	(110, 5, 5)
	B	(45, 2, 2)	(47, 2, 2)	(8, 1, 1)	(100, 5, 5)
	C	(23, 2, 2)	(26, 2, 2)	(6, 1, 1)	(55, 5, 5)

5.2. Solution. In this section, we take scenario (III) as the example to show the detailed solution process. First of all, we set the decision-makers' confidence levels for the upper and lower level chance constraints as 0.9; that is, $\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 0.9$; then the following steps are taken to determine the solution.

Step 1. We use LINGO software to solve (27) and (30) to, respectively, obtain the maximum and minimum values for the objective function F_1. The maximum value is 28218 CNY and the minimum value is −2911 CNY. Similarly, the rest of the objectives' minimum and maximum values can be determined in a similar way; the detailed results for which are shown in Table 4.

Step 2. We use (33) to obtain the linear satisfaction degree functions. The satisfaction degree function of the hospital is

$$\mathrm{SD}_0\left(F_1(x,y)\right) = \begin{cases} 1 & F_1(x,y) \geq 28218 \\ \dfrac{F_1(x,y)+2911}{28218+2911} & -2911 < F_1(x,y) \leq 28218 \\ 0 & F_1(x,y) < -2911. \end{cases} \tag{35}$$

Table 4: Objective values for the minimum and maximum values.

Objective	Result	
	Minimum values	Maximum values
Hospital's profit	−2911	28218
Department A's profit	−1092	8895.5
Department B's profit	−1083	11471
Department C's profit	−736	7851.5
Department A's capacity surplus	0	96
Department B's capacity surplus	0	84
Department C's capacity surplus	0	48

The satisfaction degree functions of the profit objectives for every department are

$$\begin{aligned} &\mathrm{SD}_1^1\left(f_1^1(x,y)\right) \\ &= \begin{cases} 1 & f_1^1(x,y) \geq 8895.5 \\ \dfrac{f_1^1(x,y)+1092}{8895.5+1092} & -1092 < f_1^1(x,y) \leq 8895.5 \\ 0 & f_1^1(x,y) < -1092, \end{cases} \\ &\mathrm{SD}_2^1\left(f_2^1(x,y)\right) \\ &= \begin{cases} 1 & f_2^1(x,y) \geq 11471 \\ \dfrac{f_2^1(x,y)+1083}{11471+1083} & -1083 < f_2^1(x,y) \leq 11471 \\ 0 & f_2^1(x,y) < -1083, \end{cases} \\ &\mathrm{SD}_3^1\left(f_3^1(x,y)\right) \\ &= \begin{cases} 1 & f_3^1(x,y) \geq 7851.5 \\ \dfrac{f_3^1(x,y)+736}{7851.5+736} & -736 < f_3^1(x,y) \leq 7851.5 \\ 0 & f_3^1(x,y) < -736. \end{cases} \end{aligned} \tag{36}$$

The satisfaction degree functions of the surplus capacity objectives for every department are

$$\mathrm{SD}_1^2\left(f_1^2(x,y)\right) = \begin{cases} 1 & f_1^2(x,y) \leq 0 \\ \dfrac{96-f_1^2(x,y)}{96-0} & 0 < f_1^2(x,y) \leq 96 \\ 0 & f_1^2(x,y) > 96, \end{cases}$$

Table 5: Appointment schedule for scenario (III) with part time doctors.

Department	Doctor	Time slots											
		1	2	3	4	5	6	7	8	9	10	11	12
A	FT Doctor 1	I3	I3	I3	I3	I2	I2	I2	I2	I1	I2	I2	I2
	FT Doctor 2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2
	FT Doctor 3	I1	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2
	FT Doctor 4	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2
	FT Doctor 5	I2	I2	I2	I2	I2	I2	I1	I1	I3	I1	I1	I1
	PT Doctor 1	I2	I2	I2	I1	I1	I1	I1	I1	I1	I1	I1	I1
	PT Doctor 2	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1
	PT Doctor 3	Not used											
B	FT Doctor 1	I2	I2	I2	I2	I2	I2	I2	I3	I3	I2	I2	I2
	FT Doctor 2	I2	I2	I2	I2	I2	I2	I1	I1	I1	I3	I3	I3
	FT Doctor 3	I3	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2
	FT Doctor 4	I2	I2	I1	I1	I1	I1	I1	I2	I2	I2	I2	I2
	FT Doctor 5	I2	I2	I2	I2	I2	I2	I2	I1	I1	I1	I1	I1
	PT Doctor 1	I2	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1	I1
	PT Doctor 2	I1	I1	I1	I1	I1	I1	I1	I1	I2	I2	I2	I2
C	FT Doctor 1	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2	I2
	FT Doctor 2	I1	I1	I2	I2	I2	I3	I3	I1	I2	I1	I2	I1
	FT Doctor 3	I2	I1	I3	I3	I3	I2	I1	I2	I1	I1	I1	I1
	PT Doctor 1	I1	I1	I1	I1	I1	I1	I1	I1	I1			

$$\mathrm{SD}_2^2\left(f_2^2(x,y)\right) = \begin{cases} 1 & f_2^2(x,y) \le 0 \\ \dfrac{84 - f_2^2(x,y)}{84 - 0} & 0 < f_2^2(x,y) \le 84 \\ 0 & f_2^2(x,y) > 84, \end{cases}$$

$$\mathrm{SD}_3^2\left(f_3^2(x,y)\right) = \begin{cases} 1 & f_3^2(x,y) \le 0 \\ \dfrac{48 - f_3^2(x,y)}{48 - 0} & 0 < f_3^2(x,y) \le 48 \\ 0 & f_3^2(x,y) > 48. \end{cases} \tag{37}$$

Step 3. When the upper level decision-makers' satisfaction degree objective is set as 0.9, model (34) is used to generate the optimization results: Department A needs 5 full time doctors and 2 part time doctors to treat 84 patients and the profit is 8317 CNY. Department B uses 5 full time doctors and 2 part time doctors to treat 84 patients and the profit is 11471 CNY. Department C uses 3 full time doctors and 1 part time doctor to treat 45 patients and the profit is 7851.5 CNY. The optimized profit of the hospital is 27639.5 CNY. The detailed appointment schedule is shown in Table 5, in which FT and PT doctor mean full time and part time doctor, respectively.

Note that, in Table 5, each time slot of every doctor in a department has been designated to a certain class of patients. Then patients will make appointment on a first-come-first-served basis. Once a time slot has been chosen by a patient, the later patients will not be able to make an appointment in this time slot any more.

5.3. Comparative Analysis. In this section, we solve the problem under four scenarios. Since this paper considers two kinds of doctors, full time doctors and part time doctors, for the scenario that the demand exceeds the total available capacity, we conduct two experiments. The first is the experiment without part time doctors, and the second is that with part time doctors.

Table 6 presents a detailed information on the results by the bilevel hospital outpatient appointment scheduling model for four kinds of scenarios. For example, let us consider the case where department A gets a demand for (95, 5, 5), department B gets demand for (85, 5, 5), and department C gets demand for (45, 5, 5). When part time doctors are not allowed, all of the full time doctors will be used, department A will treat 60 patients, department B will treat 60 patients, department C will treat 36 patients, and the profits of these three departments are 7505, 9565, and 6849, respectively. On the other hand, when the part time doctors can be used, the number of treated patients will be increased to 84, 84, and 45, and the profits will be improved to 8317, 11471, and 7851.5, respectively.

Figure 1 describes the profits of the hospital and departments A, B, and C under different demands. It is clear that if the demand is less than the total capacity of the full time doctors, whether or not using the part time doctors does not change the profit. However, if the demand is higher than the

Table 6: Doctor utilization and optimized profits under different scenarios.

Scenario	Department	Demand	Doctor		Total capacity	Optimized results						
			Full time	Part time		Used doctor		Profit	Treated patients				Hospital's profit
						Full time	Part time		I1	I2	I3	Total	
(I)	A	(45, 5, 5)	5	0	60	4	0	4299	17	23	2	42	14022.5
	B	(45, 5, 5)	5	0	60	4	0	6311.5	20	23	2	45	
	C	(20, 5, 5)	3	0	36	2	0	3412	10	10	0	20	
(II)	A	(60, 5, 5)	5	0	60	5	0	6355	22	35	3	60	21305.5
	B	(60, 5, 5)	5	0	60	5	0	8665	25	30	5	60	
	C	(35, 5, 5)	3	0	36	3	0	6285.5	15	18	2	35	
(III)	A	(95, 5, 5)	5	0	60	5	0	7505	2	52	6	60	23919
	B	(85, 5, 5)	5	0	60	5	0	9565	8	46	6	60	
	C	(45, 5, 5)	3	0	36	3	0	6849	11	20	5	36	
(III)	A	(95, 5, 5)	5	3	96	5	2	8317	28	51	5	84	27639.5
	B	(85, 5, 5)	5	2	84	5	2	11471	32	46	6	84	
	C	(45, 5, 5)	3	1	48	3	1	7851.5	20	20	5	45	
(IV)	A	(110, 5, 5)	5	0	60	5	0	7705	0	52	8	60	24769
	B	(100, 5, 5)	5	0	60	5	0	9815	5	47	8	60	
	C	(55, 5, 5)	3	0	36	3	0	7249	4	26	6	36	
(IV)	A	(110, 5, 5)	5	3	96	5	3	9148	36	52	8	96	29521
	B	(100, 5, 5)	5	2	84	5	2	11721	29	47	8	84	
	C	(55, 5, 5)	3	1	48	3	1	8652	16	26	6	48	

total capacity of the full time doctors, the profit with part time doctors is much higher than that without part time doctors.

5.4. Managerial Insights. Based on the above discussion, we can find out the following managerial insights which can be used in real-life problems:

(1) In the case that the demand exceeds the available capacity, it is not possible to satisfy the demand with the full time doctors. Then the hospital should consider employing part time doctors, so that the maximum profit can be improved obviously by meeting the excess demand, although the payment for the part time doctors is always higher than the full time doctors.

(2) More profit can be generated by increasing the total capacity. The hospitals are advised to develop other different feasible ways to make the capacity higher, for example, training the doctors to treat more patients in a given time period or encouraging working overtime to open more time slots.

(3) As all action is based on the patient demand estimation, the hospital needs to have enhanced forecasting abilities to determine to what extent the demand exceeds the capacity.

(4) Patients with different insurances will bring varying revenue to the hospital. In order to increase the revenue, the class of patients which can generate higher revenue will have utmost priority and can have access to the entire capacity available in the hospital. However, the hospital has to pay attention to the discrimination and ethical issues.

(5) Revenue management may not be applicable to cases when there is no significant difference in the revenue contribution.

6. Conclusion

This paper investigated the appointment scheduling problem based on the revenue of the hospital outpatient department under the uncertain environment and proposed an appointment scheduling model based on revenue management. After the effective transformation, the model was transformed into a solvable final model. It also obtained the number of appointments needed, the number of full time and part time doctors needed, and the maximum benefits. The comparative analysis on optimization results under different scenarios was also conducted. The following contributions were made on hospital outpatient appointment scheduling:

(i) This paper effectively characterized the uncertainties by using triangular fuzzy variables and introduced them into a bilevel programming. The upper level decision maker is the hospital that determines the used doctors; and the lower level is the departments who make the appointment scheduling based on usable doctors. The proposed bilevel programming can handle two kinds of decision maker simultaneously in a unified decision making system. And fuzzy number was adopted to replace the concrete data to get the results closest to the real-life situation.

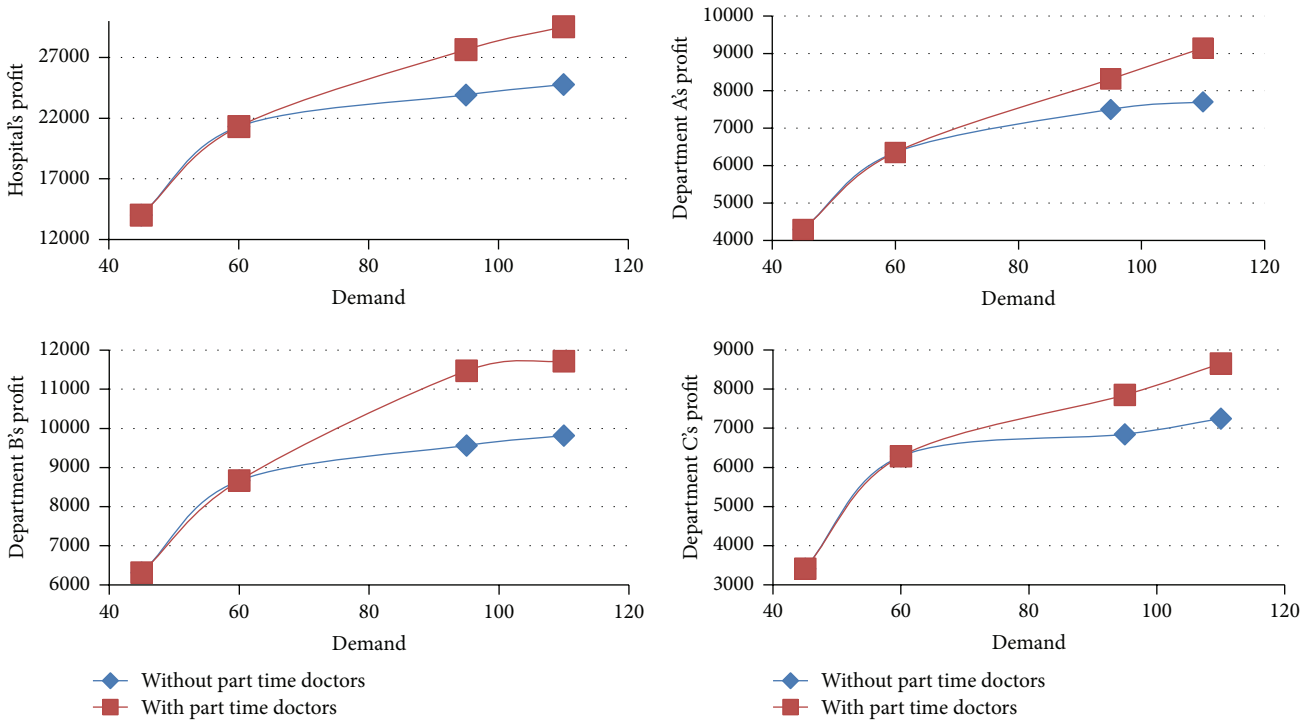

Figure 1: Profits under different demands.

(ii) The paper investigated two important factors in hospital outpatient appointment scheduling problem. The first is the patient classification. We divided the patients into three classes based on the insurance they hold. Different revenue will be generated by using different insurance. The second is the employment of the part time doctors. We compared the results with the part time doctors and that without the part time doctors and drew several interesting conclusions.

It has been found that if we extend the capacity, more patients will be treated and thus higher profit can be realized. The future research may focus on another way of increasing capacity: a doctor can give treatments to more than one patient at the same time, which means groups treatment can be adopted. Based on this, this research can be extended to identify an optimal mix of patients that can be grouped together so that the total profit of the outpatient clinic is maximized.

Competing Interests

The authors declare that they have no competing interests.

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Research Article

A Novel Multiobjective Programming Model for Coping with Supplier Selection Disruption Risks under Mixed Uncertainties

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Supply chain has become more and more vulnerable to disruption since it is suffering widespread risk issues from inside or outside. Higher uncertainties in the supplier selection problem have gone beyond the traditional cost minimization concern. These uncertainties are related to an ever increasing product variety, more demanding customers, and a highly interconnected distribution network. This paper focuses on the supplier selection problem with disruption risks and mixed uncertainties. A novel multiobjective optimization model with mixed uncertain coefficients is developed, which maximizes the total profits and minimizes the percentage of items delivered late, percentage of items rejected, and total loss cost due to supplier dysfunction. Meanwhile, we also consider the customer demand to be a random fuzzy variable and the unit purchase cost to be a fuzzy variable. By examining a numerical example, we found that the confidence level and demand of customers have impact on the quantities purchased by customers from suppliers although the distribution of suppliers will not change. The cost, quality, and service also influence the selection of suppliers. The superevents have little influence on the distribution of supplier selection; however, when unique event occurs, the distribution of supplier selection will change.

1. Introduction

Risks and uncertainties existing in supply chain increase the analytically complexity, which usually leads to the huge loss or supply chain disruption. Besides the profit, delivered late, and percentage of items rejected, risk and uncertainty management is of key importance to reduce the supply chain vulnerability. There is a common consensus that many sources of threats result in a sharp increase of supplier selection risk in a global supply chain system. For example, the occurrence of disasters and political conflicts could create supply chain disruptions. Some inherent uncertain factors in traditional supply chain such as high supply and demand uncertainties during the operating process make it hard to avoid the risk in supply chain.

Supply chain risks are usually divided into two categories: (i) disruption risks and (ii) operational risks [1]. Focusing on the supplier selection problem, there is no doubt that disruption risk management is one of the critical activities for firms to ensure their effectiveness and competitiveness and achieve the objectives of the whole supply chain. Berger et al. [2] introduced a decision tree model to consider supplier selection under risk and uncertainty in order to identify the optimal number of suppliers in the supply chain. In their work, two types of risks are discussed: catastrophic super events that affect all suppliers and unique events which affect a single supplier. Sawik [3] proposed a stochastic mixed-integer programming approach to cope with joint supplier selection and scheduling problem under disruption risks. Sawik [4] also addressed a fair optimization of cost and customer service level in the presence of supply chain disruption risks. Hamdi et al. [5] presented two integer programming models to determine the supplier selection and order allocation in the presence of disruption risk supplier. Torabi et al. [6] developed a biobjective mixed possibilistic, two-stage stochastic programming model to address supplier

selection and order allocation problem to build the resilient supply base under operational and disruption risks. Fahimnia et al. [7] presented a systematic review of the quantitative and analytical models for managing supply chain risks and found that sustainability risk analysis is an emerging and fast evolving research topic. Heckmann et al. [8] studied the review of the definition, measure, and modeling of supply chain risks. Wiengarten et al. [9] explored the role of risk and risk management practices of supply chain integration and found that supplier integration is also effective in weak rule of law (i.e., high risk) environments. The above researches about supply chain risks concentrate on some general nodes of a supply chain but not a type of supply problems with special characteristics. In this paper, we employ three types of risk situation to measure the disruption risk of supplier selection problem: "superevents" such as terrorism or a widespread airline action that put all suppliers down; "unique event" uniquely associated with a particular supplier that puts it down during the supply cycle; and "semisuperevents" that affect a subset of all suppliers, but more than one and not all suppliers.

Higher uncertainties in the supplier selection problem have gone beyond the traditional cost minimization concern. These uncertainties are related to an ever increasing product variety, more demanding customers, and a highly interconnected distribution network. Research on uncertainties in supply chain systems is a timely and important topic nowadays in both academia and industry, and some quantitative models have been gradually developed [10–12]. Memon et al. [13] claimed that supplier selection is highly associated with recognitive and stochastic uncertainties and depends on large amount of domain knowledge. Amorim et al. [14] proposed an integrated framework to determine the supplier in the processed food industry under uncertainty. Moghaddam [15] developed a fuzzy multiobjective mathematical model for decision making of supplier selection under supply and demand uncertainty. Azaron et al. [16] developed a multiobjective stochastic programming approach for minimizing the financial risk or the probability of not meeting a certain budget in a supply chain system under uncertainty. Dickson [17] initially stated five criteria of supplier selection including quality, delivery, performance history, warranty policy, and supplier's production capacity. Some recent researches identified that as quality, cost, and delivery performance history [18], or cost, quality, and time response [19]. Gaballa [20] developed a single-objective, mixed-integer programming model to minimize the total cost. Ghodsypour and O'Brien [21] took the price, storage, and order cost as well as transportation into consideration and developed a mixed-integer nonlinear programming model for minimizing total cost. However, in the practical problems, most of the input parameters are inaccurate, or some of the factors are uncertain. The uncertainty usually results in the widespread risk issues within or external to the supplier selection of a supply chain system. Aghai et al. [22] developed a fuzzy multiobjective programming model containing quantitative and qualitative risk factors as well as quantity discount to propose supplier selection. In their model, late items, rejected items, environment conditions, and vendor rate are set as qualitative factors (fuzzy), and just unit cost is modeled as quantitative factor. Wu et al. [23] considered both qualitative and quantitative risk factors including vendor ratings, cost, quality, and logistics, which were formulated by some fuzzy data, to decide on supplier selection.

In contrast to much of the extant literature, the contribution and innovation of this paper can be summarized as follows:

(i) Three types of risk events for supplier selection in a supply chain system are introduced: (i) the superevents; (ii) when all suppliers close down during the supply cycle; and (iii) when some, but not all the suppliers, close down.

(ii) We explore a mixed-uncertain situation for supplier selection, in which the customer demand is considered to be a random fuzzy variable and customers' purchase cost, percentage of items being late, and percentage of rejected items are considered to be fuzzy variables.

(iii) A novel multiobjective programming with mixed uncertain coefficients is developed for coping with the supplier selection disruption risk. The proposed model simultaneously maximizes the total profits and minimizes the percentage of items delivered late, percentage of items rejected, and the total loss cost due to supplier dysfunction.

The structure of this paper is as follows: after introducing three types of risk events for supplier selection in a supply chain system, a novel multiobjective programming with mixed uncertain coefficients is developed for coping with the supply chain risk in Section 2; Section 3 presents a comprised solution-based GA to solve the proposed multiobjective programming model; Section 4 examines a numerical example to show the effectiveness of the proposed model; and Section 5 draws the conclusions of the study.

2. Supply Chain Risk Modelling

2.1. Problem Statement and Notations. Supply chain risk management is usually discussed from the four perspectives: (i) disruption risk management, (ii) operational risk control, (iii) disaster and emergency management, and (iv) supply chain service risk analysis. In this study, a supplier selection problem in supply chain systems with disruption risks and uncertainties is considered. In the present problem, three types of risk situations are considered: "*superevents*" such as terrorism or a widespread airline action that put all suppliers down; "*unique event*" uniquely associated with a particular supplier that puts it down during the supply cycle; and "*semisuperevents*" that affect a subset of all suppliers, but more than one and not all suppliers. Following that, a total loss cost objective due to supplier dysfunction is considered in the supplier selection problem. Besides, three traditional objectives including maximizing the total profits and minimizing the percentage of items delivered late and

percentage of items rejected are also considered to optimize the selection of suppliers.

In addition to the above complications, there is a great level of inherent uncertainty involved with customers' demand, customers' purchase cost, percentage of items being late, and percentage of rejected items that should be addressed in the decision making context in supplier selection problems. Customers' demand is usually estimated by large amount of historical data and expert's assessment, so it is formulated by a random fuzzy variable. Customers' purchase cost, percentage of items being late, and percentage of rejected items usually depend on large amount of domain knowledge where expert's assessment plays an important role when decision makers have lack of knowledge or small availability of information for different set of suppliers. Therefore, they are assumed as fuzzy variables which are widely used to handle the recognitive uncertainty.

To model and solve the above complex supplier selection problem with disruption risks and mixed uncertainties, a multiobjective mathematical model with mixed uncertain coefficients is formulated by using the following notations for sets, indices, decision variables, and parameters.

Indices

i: index for the customer

j: index for the supplier

Parameters

n_i: number of candidate suppliers required by the ith customer

s_i: unit selling price for the ith customer

c_{ij}: unit purchase cost from supplier j by the ith customer

λ_{ij}: percentage of items being late from supplier j to the ith customer

k: unit cost of items being late

τ_{ij}: percentage of rejected items from supplier j

l: unit cost of rejected items

D_i: demand for item over planning period from the ith customer

u_{ij}: maximum amount for the item to be given to supplier j by the ith customer

w_{ij}: maximum order quantity from supplier j by the ith customer

π_0: probability of one of the superevents occurring in a supply cycle

π_j: probability of the unique event occurring in a supply cycle for supplier j

I_0: random indicator associated with the superevents

I_j: random indicator associated with the unique event for supplier j

Decision Variables

x_{ij}: quantity purchased by the ith customer from supplier j

2.2. Modeling. Many traditional models due to the lack of consideration of various demand risks from many different customers usually consider the following objectives and constraints [24]:

Objective 1: maximize the expected value of total profits comprised by income and costs

Objective 2: maximize the utility of the number of or rejected items

Objective 3: maximize the utility of the number of late deliveries

Constraint 4: ensure that the quantity demand is met

Constraint 5: ensure that the customer's proposed business to the vendor is not exceeded

Constraint 6: establish minimum business for selected vendors

Constraint 7: ensure that there are no negative orders.

A deterministic multiobjective programming model (LMOP) for the supplier selection is presented as follows:

$$\begin{aligned}
&\max \quad f_1\left(x_{ij}\right) = \sum_{i=1}^{m} D_i s_i - \sum_{i=1}^{m}\sum_{j=1}^{n_i} c_{ij}x_{ij} \quad \{\#\text{total profits}\}\\
&\min \quad f_2\left(x_{ij}\right) = l\sum_{i=1}^{m}\sum_{j=1}^{n_i} \tau_{ij}x_{ij} \quad \{\#\text{rejected}\}\\
&\min \quad f_3\left(x_{ij}\right) = k\sum_{i=1}^{m}\sum_{j=1}^{n_i} \lambda_{ij}x_{ij} \quad \{\#\text{late}\}\\
&\text{subject to:} \quad \sum_{j=1}^{n_i} x_{ij} \geq D_i, \quad i = 1,\ldots,m\\
&\qquad x_{ij} \leq u_{ij}\\
&\{\#\text{upper business bound set for the purchased amount}\}, \ \forall i, j\\
&\qquad x_{ij} \leq w_{ij}\\
&\{\#\text{upper order bound for the purchased amount}\}, \ \forall i, j\\
&\qquad x_{ij} \geq 0,
\end{aligned} \tag{1}$$

where $j = 1, 2, \ldots, n$ represents the possible vendors selected for the ith customer. The model LMOP (1) simultaneously maximizes the total profits ($f_1(x_{ij})$) and minimizes the percentage of items delivered late ($f_2(x_{ij})$) and percentage of items rejected ($f_3(x_{ij})$), while satisfying various constraints with respect to the order quantities.

When any of the above three types of risk situations takes place, the core company, that is, supplier partner, will suffer some loss. The event triggering the loss comes from three sources: (i) the superevents; (ii) when all suppliers close down during the supply cycle; and (iii) when some, but not all the suppliers, close down. We denote by I_0 and I_j the indicator random variable associated with the former two risk situations, respectively. We use $J \in 1, 2, \ldots, n_i$ and π_j to denote the probability of the superevent occurring and unique event occurring for supplier j during the supply cycle, respectively; that is, probability$(I_0 = 1) = P$ and

probability($I_j = 1$) $= \pi_j$. We denote L_{0j} to be the unit financial loss due to either the superevent occurring on the jth supplier or when all suppliers close down, and we denote by L_P the unit financial loss when some, but not all suppliers, close down.

The first two cases result in the total loss ($x_{ij}L_{0j}$) and the last case results in partial loss ($x_{ij}L_P$). Thus, the loss cost associated with each set of suppliers n_i can be represented by

$$\begin{aligned} f(J) &= \left[I_0 + (1 - I_0)\prod_{j\in J} I_j\right]\sum_{j\in J}\left(L_{0j}x_{ij}\right) \\ &\quad + \left[1 - \prod_{j\in J} I_j - \prod_{j\in J}\left(1 - I_j\right)\right](1 - I_0)\sum_{j\in J}\left(L_P x_{ij}\right). \end{aligned} \tag{2}$$

Choi et al. [1] argue that omission of "semisuperevents" loss greatly simplifies the computation while it does not materially affect the salient issues to be analyzed and discussed. When "semisuperevents" loss is omitted, the total loss cost function is reduced to

$$f_4\left(x_{ij}\right) = \left[I_0 + (1 - I_0)\prod_{j=1}^{n_i} I_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right). \tag{3}$$

To consider catastrophic, "superevents," which affect many/all suppliers, and "unique events" that affect only a single supplier, we develop the following four-objective programming models by adding objective of minimizing $f_4(x_{ij})$ into the first programming model.

$$\begin{aligned} \max\quad & f_1\left(x_{ij}\right) = \sum_{i=1}^{m} D_i s_i - \sum_{i=1}^{m}\sum_{j=1}^{n_i} c_{ij}x_{ij} \\ \min\quad & f_2\left(x_{ij}\right) = l\sum_{i=1}^{m}\sum_{j=1}^{n_i}\tau_{ij}x_{ij} \\ \min\quad & f_3\left(x_{ij}\right) = k\sum_{i=1}^{m}\sum_{j=1}^{n_i}\lambda_{ij}x_{ij} \\ \min\quad & f_4\left(x_{ij}\right) \\ & \quad = \left[I_0 + (1 - I_0)\prod_{j=1}^{n_i} I_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right) \\ \text{subject to:}\quad & \sum_{j=1}^{n_i} x_{ij} \geq D_i, \quad i = 1, \ldots, m \\ & x_{ij} \leq u_{ij}, \quad \forall i, j \\ & x_{ij} \leq w_{ij}, \quad \forall i, j \\ & x_{ij} \geq 0, \end{aligned} \tag{4}$$

where $j = 1, 2, \ldots, n_i$ represents the possible vendors selected for the ith customer. The above model simultaneously maximizes the total profits ($f_1(x_{ij})$) and minimizes the percentage of items delivered late ($f_2(x_{ij})$), percentage of items rejected ($f_3(x_{ij})$), and the total loss cost ($f_4(x_{ij})$) due to supplier dysfunction, while satisfying various constraints with respect to minimum and maximum order quantities.

Customers' demand, which is formulated by a random fuzzy variable, is usually estimated by large amount of historical data and expert's assessment simultaneously. Customers' purchase cost, percentage of items being late, and percentage of rejected items are assumed to be fuzzy variables to handle the recognitive uncertainty due to lack of knowledge and historical data of different set of suppliers. Hence, we suggest a mixed MOP model by allowing $\tilde{\simeq}\ D_i$ to be random fuzzy variable and some parameters in the above model to be fuzzy data [25–28].

$$\begin{aligned} \max\quad & f_1\left(x_{ij}\right) = \sum_{i=1}^{m} \tilde{\simeq}\ D_i\ s_i - \sum_{i=1}^{m}\sum_{j=1}^{n_i}\tilde{c}_{ij}x_{ij} \\ \min\quad & f_2\left(x_{ij}\right) = l\sum_{i=1}^{m}\sum_{j=1}^{n_i}\tilde{\tau}_{ij}x_{ij} \\ \min\quad & f_3\left(x_{ij}\right) = k\sum_{i=1}^{m}\sum_{j=1}^{n_i}\tilde{\lambda}_{ij}x_{ij} \\ \min\quad & f_4\left(x_{ij}\right) \\ & \quad = \left[I_0 + (1 - I_0)\prod_{j=1}^{n_i} I_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right) \\ \text{subject to:}\quad & \sum_{j=1}^{n_i} x_{ij} \geq \tilde{\simeq}\ D_i, \quad i = 1, \ldots, m \\ & x_{ij} \leq u_{ij}, \quad \forall i, j \\ & x_{ij} \leq w_{ij}, \quad \forall i, j \\ & x_{ij} \geq 0, \end{aligned} \tag{5}$$

where "$\simeq$" denotes a random fuzzy variable and "$\sim$" denotes fuzzy variable.

Theorem 1. *Assume that the random variable $\overline{D}_i(\theta)$ is characterized by the following density function:*

$$P_{\overline{D}_i}(x) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-(x-\tilde{\mu}_i(\theta))^2/2\sigma_i^2}, \tag{6}$$

where the fuzzy variable $\tilde{u}_i(\theta)$, $\theta \in \Theta$, has the following membership function:

$$\mu_{\tilde{u}_i^D(\theta)}(t) = \begin{cases} L\left(\dfrac{b_i^D - t}{a_i^D}\right), & t \leq b_i^D,\ a_i^D > 0 \\ R\left(\dfrac{t - b_i^D}{c_i^D}\right), & t \geq b_i^D,\ c_i^D > 0, \end{cases} \tag{7}$$

where a_i^D, c_i^D *are positive numbers expressing the left and right spreads of* b_i^D *which is the average value of* $\widetilde{u}_i$. *Functions* $L, R : [0,1] \to [0,1]$ *with* $L(1) = R(1) = 0$ *and* $L(0) = R(0) = 1$ *are nonincreasing continuous functions. Then we have*

$$E\left(\tilde{\tilde{D}}_i\right) = b_i^D + \frac{a_i^D}{2}\left[F_L\left(b_i^D\right) - F_L\left(a_i^D\right)\right] + \frac{c_i^D}{2}\left[F_R\left(b_i^D\right) - F_R\left(c_i^D\right)\right], \tag{8}$$

where $F_L(x)$ *and* $F_R(x)$ *are continuous functions while* $F_L'(x) = L(x)$, $x \in [a_i^D, b_i^D]$, *and* $F_R'(x) = L(x)$, $x \in [b_i^D, c_i^D]$.

Proof. The proof can be found in Appendix A. □

Theorem 2. *Assume that the fuzzy parameter* $\widetilde{c}_{ij}$ *is a triangular fuzzy variable, denoted by* $(a_{ij}^c, b_{ij}^c, c_{ij}^c)$, $a_{ij}^c > 0$. *Then we have*

$$E\left[f_4\left(x_{ij}\right)\right] = \left[p\prod_{j=1}^{n_i}\left(1-\pi_j\right) + (1-p)\prod_{j=1}^{n_i}\pi_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right) \tag{9}$$

and for $0 \le \alpha_i, \beta_i \le 1$,

$$\begin{aligned} &\mathrm{Ch}\left\{\tilde{\tilde{D}}_i \le \sum_{j=1}^{n_i} x_{ij}\right\}(\alpha_i) \ge \beta_i \Longleftrightarrow \\ &b_i^D \ge \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \\ &\quad \ge \max\left\{a_i^D, b_i^D - a_i^D L^{-1}(\alpha_i)\right\}. \end{aligned} \tag{10}$$

Proof. The proof can be found in Appendix A. □

Finally, the proposed novel multiobjective programming model for supply chain risk management under mixed uncertainty can be converted into the following deterministic one:

$$\begin{aligned} \max \quad & f_1\left(x_{ij}\right) = E\left(\sum_{i=1}^{m}\tilde{\tilde{D}}_i\, s_i - \sum_{i=1}^{m}\sum_{j=1}^{n_i}\widetilde{c}_{ij}x_{ij}\right) \\ \min \quad & f_2\left(x_{ij}\right) = E\left(l\sum_{i=1}^{m}\sum_{j=1}^{n_i}\widetilde{\tau}_{ij}x_{ij}\right) \\ \min \quad & f_3\left(x_{ij}\right) = E\left(k\sum_{i=1}^{m}\sum_{j=1}^{n_i}\widetilde{\lambda}_{ij}x_{ij}\right) \\ \min \quad & f_4\left(x_{ij}\right) \\ & = \left[p\prod_{j=1}^{n_i}\left(1-\pi_j\right) + (1-p)\prod_{j=1}^{n_i}\pi_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right) \\ \text{subject to:} \quad & b_i^D \ge \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \\ & \ge \max\left\{a_i^D, b_i^D - a_i^D L^{-1}(\alpha_i)\right\} \\ & \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \ge b_i^D, \\ & \qquad i = 1, \ldots, m,\ \alpha_i \ge 0,\ \beta_i \ge 0 \\ & x_{ij} \le \min\left\{u_{ij}, w_{ij}\right\} \quad \forall i, j \\ & x_{ij} \ge 0, \end{aligned} \tag{11}$$

where $E(\tilde{\tilde{D}}_i) = b_i^D + (a_i^D/2)[F_L(b_i^D) - F_L(a_i^D)] + (c_i^D/2)[F_R(b_i^D) - F_R(c_i^D)]$, $E(\widetilde{c}_{ij}) = (a_{ij}^c + 2b_{ij}^c + c_{ij}^c)/4$, $E(\widetilde{\beta}_{ij}) = (a_{ij}^\beta + 2b_{ij}^\beta + c_{ij}^\beta)/4$, and $E(\widetilde{\lambda}_{ij}) = (a_{ij}^\lambda + 2b_{ij}^\lambda + c_{ij}^\lambda)/4$.

3. Comprised Solution-Based Genetic Algorithm

Genetic algorithms (GAs) have received considerable attention regarding their potential for providing a novel approach to multiobjective optimization problems, resulting in a fresh body of research and applications known as genetic multiobjective optimizations. For many real world problems, the set of Pareto solutions may be very large, so it is hard to solve them. In addition, to evaluate a large set of Pareto solutions and to select the best one pose a considerable cognitive burden on the decision maker. Therefore, in this case, obtaining the entire set of Pareto solutions is of little interest to decision makers. For overcoming such difficulties, Gen and Cheng [29] proposed a compromise approach which aims to search for compromise solutions instead of generating all Pareto solutions.

The compromise approach can be regarded as a kind of mathematical formulation of goal-seeking behavior in terms of a distance function. In this case, the compromise approach is given as follows: Suppose the ideal point of the decision maker is $f_k^*(x_{ij})$. For each feasible solution x_{ij}, the regret function $r(x_{ij}, 2)$ is defined as follows:

$$r\left(x_{ij}, 2\right) = \left[\sum_{k=1}^{4} w_k^2\left(f_k\left(x_{ij}\right) - f_k^*\left(x_{ij}\right)\right)^2\right]^{1/2}, \tag{12}$$

where weights $w = (w_1, w_2, w_3, w_4)$ are assigned to signal different degrees of importance. Hereby, we use a proxy ideal point introduced by Ghodsypour and O'Brien [21] to replace the ideal point $f_k^*(x_{ij})$. Above all, we illustrate the compromise solution-based genetic algorithm procedure as follows and the pseudocodes can be found in Appendix B.

Step 0. Input the parameters including the number of chromosomes ($N_{\text{pop-size}}$), crossover probability (P_λ), and mutation probability (P_m).

Step 1. Initialize $N_{\text{pop-size}}$ chromosomes by randomly searching in the feasible region.

Table 1: Some parameters ($\widetilde{c}_{ij}$, $\widetilde{\tau}_{ij}$, $\widetilde{\lambda}_{ij}$) for suppliers and customers.

	1	2	3	4	5
	(0.8, 0.9, 1)	(0.7, 0.75, 0.8)	(0.93, 0.97, 1.01)	(0.8, 0.86, 0.92)	(0.55, 0.58, 0.61)
1	(0.008, 0.01, 0.012)	(0.018, 0.02, 0.022)	(0.013, 0.014, 0.015)	(0.025, 0.027, 0.029)	(0.016, 0.017, 0.018)
	(0.01, 0.02, 0.03)	(0.027, 0.03, 0.033)	(0.023, 0.025, 0.027)	(0.018, 0.02, 0.022)	(0.04, 0.041, 0.042)
	(0.86, 0.85, 0.87)	(0.59, 0.6, 0.61)	(0.84, 0.85, 0.86)	(0.98, 0.99, 0.1)	(0.97, 0.98, 0.99)
2	(0.01, 0.011, 0.012)	(0.02, 0.021, 0.022)	(0.03, 0.037, 0.041)	(0.005, 0.0051, 0.0052)	(0.06, 0.061, 0.062)
	(0.01, 0.02, 0.03)	(0.031, 0.033, 0.035)	(0.031, 0.032, 0.033)	(0.021, 0.022, 0.023)	(0.03, 0.04, 0.05)
	(1, 1.01, 1.02)	(0.84, 0.87, 0.9)	(0.9, 0.91, 0.92)	(0.99, 1, 1.01)	(1.01, 1.02, 1.03)
3	(0.027, 0.028, 0.029)	(0.014, 0.015, 0.016)	(0.018, 0.02, 0.022)	(0.008, 0.01, 0.012)	(0.025, 0.027, 0.029)
	(0.018, 0.02, 0.022)	(0.032, 0.035, 0.038)	(0.027, 0.03, 0.033)	(0.01, 0.02, 0.03)	(0.033, 0.04, 0.047)
	(0.91, 0.93, 0.95)	(0.9, 0.92, 0.94)	(0.98, 1, 1.02)	(1, 1.02, 1.04)	(0.96, 0.98, 1)
4	(0.021, 0027, 0.033)	(0.02, 0.03, 0.04)	(0.005, 0.0051, 0.0052)	(0.03, 0.037, 0.041)	(0.0134, 0.0135, 0.0136)
	(0.02, 0.024, 0.028)	(0.022, 0.024, 0.026)	(0.025, 0.029, 0.034)	(0.01, 0.02, 0.03)	(0.034, 0.036, 0.038)
	(0.98, 1, 1.02)	(0.96, 0.98, 1)	(1.01, 1.03, 1.05)	(1, 1.02, 1.04)	(1.02, 1.03, 1.04)
5	(0.008, 0.01, 0.012)	(0.02, 0.021, 0.022)	(0.008, 0.01, 0.012)	(0.01, 0.011, 0.012)	(0.027, 0.028, 0.029)
	(0.015, 0.018, 0.021)	(0.032, 0.035, 0.038)	(0.032, 0.035, 0.038)	(0.017, 0.02, 0.023)	(0.0366, 0.037, 0.0376)
	(0.97, 1, 1.03)	(0.96, 0.97, 0.98)	(0.74, 0.76, 0.78)	(1, 1.01, 1.02)	(0.99, 1.01, 1.03)
6	(0.024, 0.026, 0.028)	(0.018, 0.02, 0.022)	(0.006, 0.0061, 0.0062)	(0.013, 0.014, 0.015)	(0.023, 0.0233, 0.0236)
	(0.015, 0.02, 0.025)	(0.027, 0.03, 0.033)	(0.02, 0.03, 0.04)	(0.023, 0.025, 0.027)	(0.03, 0.039, 0.048)
	(0.85, 0.87, 0.89)	(0.81, 0.82, 0.83)	(0.9, 0.92, 0.94)	(0.86, 0.87, 0.88)	(0.86, 0.88, 0.9)
7	(0.024, 0.0245, 0.025)	(0.026, 0.026, 0.026)	(0.03, 0.037, 0.041)	(0.008, 0.01, 0.012)	(0.022, 0.023, 0.024)
	(0.02, 0.02, 0.02)	(0.02, 0.03, 0.04)	(0.031, 0.032, 0.033)	(0.01, 0.02, 0.03)	(0.03, 0.04, 0.05)
	(0.99, 1, 1.01)	(0.98, 1, 1.02)	(1.18, 1.2, 1.22)	(0.86, 0.88, 0.9)	(0.95, 0.98, 1.01)
8	(0.01, 0.0112, 0.0124)	(0.013, 0.014, 0.015)	(0.05, 0.051, 0.052)	(0.025, 0.027, 0.029)	(0.0122, 0.0123, 0.0124)
	(0.01, 0.02, 0.03)	(0.023, 0.025, 0.027)	(0.021, 0.03, 0.039)	(0.0015, 0.019, 0.024)	(0.03, 0.04, 0.05)
	(0.99, 1, 1.01)	(0.96, 0.98, 1)	(1.01, 1.03, 1.05)	(0.58, 0.6, 0.62)	(0.73, 0.75, 0.77)
9	(0.018, 0.02, 0.022)	(0.027, 0.028, 0.029)	(0.02, 0.022, 0.024)	(0.02, 0.021, 0.022)	(0.02, 0.03, 0.04)
	(0.025, 0.03, 0.035)	(0.022, 0.024, 0.026)	(0.03, 0.033, 0.036)	(0.029, 0.03, 0.031)	(0.035, 0.039, 0.044)
	(0.99, 1, 1.01)	(1, 1.01, 1.02)	(1.02, 1.03, 1.04)	(0.96, 0.97, 0.98)	(0.98, 1.01, 1.04)
10	(0.001, 0.002, 003)	(0.008, 0.01, 0.012)	(0.013, 0.014, 0.015)	(0.023, 0.024, 0.025)	(0.052, 0.053, 0.054)
	(0.028, 0.03, 0.032)	(0.01, 0.02, 0.03)	(0.031, 0.032, 0.033)	(0.023, 0.025, 0.027)	(0.035, 0.04, 0.045)

Step 2. Update the chromosomes by crossover and mutation operations after checking the feasibility of offspring.

Step 3. Compute the fitness of each chromosome on the basis of the regret value.

Step 4. Select the chromosomes by spinning the roulette wheel.

Step 5. Repeat the second to fourth steps for a given number of cycles.

Step 6. Output the best chromosome as the optimal solution.

4. Numerical Example

A supply chain with five suppliers and ten customers is listed in Table 1, which covers the unit purchase cost from supplier j by the ith customer, percentage of items late from supplier j to the ith customer, and percentage of rejected units from supplier j. The demand $\widetilde{\widetilde{D}}_i$ assumed to be distributed as $N(\widetilde{u}_i, \sigma_i^2)$ for a given period is listed in Table 2. The retailer must anticipate demand and order quantities of the modeled good to be delivered to arrive on time at each demand destination. Profit could be obtained from sales with successfully goods delivery to each demand.

Table 2: Demand data of customers.

Customer	μ_i	σ_i	s_i
$D1$	(28, 30, 32)	1.0	10
$D2$	(26, 28, 30)	1.0	9.5
$D3$	(21, 22, 23)	1.2	10.5
$D4$	(17, 18, 19)	0.8	8
$D5$	(14.5, 15, 15.5)	0.7	7.5
$D6$	(12, 13, 14)	1.0	10
$D7$	(11, 12, 13)	0.9	9
$D8$	(11, 12, 13)	0.6	7.5
$D9$	(11.5, 12, 12.5)	0.7	9
$D10$	(11.5, 11, 11.5)	0.9	10

Table 3: Solutions with different confidence levels.

	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
$\alpha_i = 0.9$ $\beta_i = 0.9$	31.08	23.436	18.924	13.052	12.668
	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
	12.602	29.08	14.18	15.846	12.796
	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
$\alpha_i = 0.75$ $\beta_i = 0.75$	30.87	23.18	18.75	12.86	12.54
	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
	12.41	28.87	13.97	15.69	12.65
	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
$\alpha_i = 0.6$ $\beta_i = 0.6$	30.44	22.66	18.40	12.48	12.28
	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
	12.03	28.44	13.54	15.40	12.35

The corresponding selling price s_i is listed in Table 3. Costs are probabilistic as outlined above, but total cost of goods sales has a mean given for each source supplier. Goods not passing quality acceptance level are not paid for. Goods delivered late are paid for at a reduced rate and are carried forward at an inventory cost. We then set $u_{ij} = w_{ij} = 50$. Furthermore, following Choi et al. [1], we assume deterministic loss and operating cost. Therefore, we also have $L_{0j} = 50$ $(j = 1, 2, \ldots, 5)$, $P = 0.02$, and $\pi_1 = \pi_2 = \pi_3 = \pi_4 = \pi_5 = 0.05$. It is a natural state that both the probability of one of the superevents and the probability of the unique event occurring during the supply cycle for supplier are normal.

Table 1 lists the value of each triangular fuzzy parameter. For example, the set of data in the 1st row 1st column denotes the unit purchased cost $\widetilde{c}_{11}$ $(0.8, 0.9, 1)$, the percentage of rejected items $\widetilde{\tau}_{11}$ $(0.008, 0.01, 0.012)$, and the percentage of items late $\widetilde{\lambda}_{11}$ $(0.01, 0.02, 0.03)$ from the 1st supplier to the 1st customer, respectively. These data could be set by analyzing the distributing of correlative historical data collected by each supplier. Take $\widetilde{c}_{11}$, for example. The 1st supplier analyzes the data of unit purchased cost within past 10 periods and finds the data is distributed in $[0.8, 1]$. We depict it with triangular fuzzy parameter. Ten demand sites have been modeled in the same way. Different conditions could be modeled with little difficulty other than scale.

The x_{ij} in Table 3 means that the chosen supplier j by the customer i and the set of solution achieve the optimal value of objective functions. Table 3 shows that, in the condition that makes other parameters changeless, the value of solutions can be affected by the different α_i and β_i while the distributing of solutions unaltered. In the following sections, we concentrate on the influence from the parameters $\widetilde{\widetilde{D}}_i$, $\widetilde{c}_{ij}$, $\widetilde{\tau}_{ij}$, and $\widetilde{\lambda}_{ij}$ to the solutions. We fix up the parameter of confidence level ($\alpha_i = 0.9$; $\beta_i = 0.9$).

As we know, the parameter $\widetilde{\widetilde{D}}_i$ denotes the demand for item over planning period from the ith customer. $\widetilde{\widetilde{D}}_i$ is a random fuzzy variable with the mean μ_i and the variance σ_i. Different sets of μ_i and σ_i are given in Table 4 and the corresponding sets of x_{ij} are listed in Figure 1.

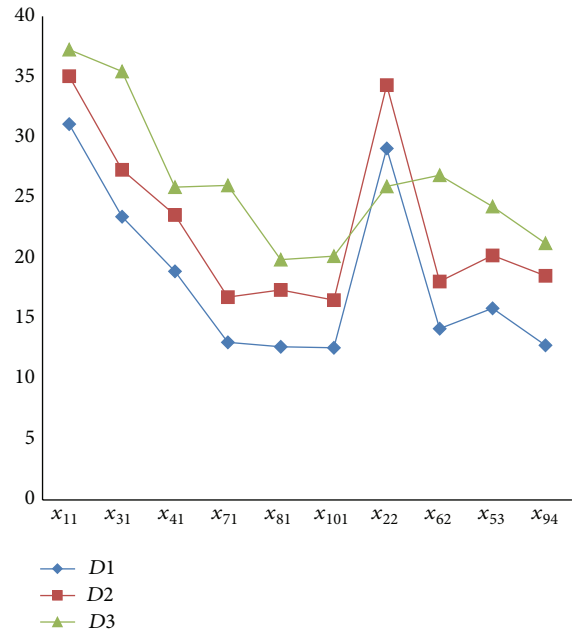

Figure 1: Solutions with different customer demands.

Parameter $\widetilde{c}_{ij}$ denotes the purchasing cost from the supplier to customers. The value of the cost always changed with the market. We assume different groups of $\widetilde{c}_{ij}$ and the results in Table 5.

In Table 5, $C1$ denotes the situation of the mean of costs of all suppliers having increased 0.1, $C2$ denotes the situation of the mean of the purchasing costs of the 1st supplier having increased 0.1, and $C3$ denotes the situation of the mean of the purchasing costs of the 1st and 2nd supplier having increased. The results show that the distribution of solutions alters along with the alteration of $\widetilde{c}_{ij}$. Videlicet, the cost is one of the factors which lead customers to select the supplier.

We then set three groups of $\widetilde{\tau}_{ij}$, the parameter of percentage of rejected items from supplier. Table 6 and Figure 2 show the results. $T1$ denote the original situation. $T2$ denote the situation of the percentage of rejected items of the 4th and 5th suppliers having been reduced and $T3$ for that of the 1st and 2nd having been increased.

The results show that the distribution of solutions varies along with the alteration of $\widetilde{\tau}_{ij}$, and the parameter of items delayed by suppliers λ_{ij} also impacts the distribution of solutions.

The foregoing computation and analysis are based on a common state that both the probability of one of the superevents and the probability of the unique event occurring during the supply cycle for supplier are normal. In Table 7, we assume three kinds of risk situations, denoted as $R1$ (the common state), $R2$ (the probability of superevents increased and all the unit financial loss L_{0j} $(j = 1, 2, \ldots, 5)$ increased accordingly), and $R3$ (the probability of unique event occurring for the 1st and 2nd supplier increased and the unit financial loss L_{01} and L_{02} altered simultaneity). Figure 3 shows the solutions.

The results show that superevents have no influence on the distribution of solutions. The customers take the same

Table 4: Different customer demands.

$\tilde{D}_{i1}$	μ_i	σ_i	$\tilde{D}_{i2}$	μ_i	σ_i	$\tilde{D}_{i3}$	μ_i	σ_i
$D1$	(30, 34, 38)	1.0	$D1$	(28, 30, 32)	1.2	$D1$	(34, 36, 32)	1.2
$D2$	(28, 32, 36)	1.0	$D2$	(26, 28, 30)	1.2	$D2$	(32, 34, 36)	1.2
$D3$	(23, 26, 29)	1.2	$D3$	(21, 22, 23)	1.4	$D3$	(33, 34, 35)	1.4
$D4$	(19, 22, 25)	0.8	$D4$	(17, 18, 19)	1.0	$D4$	(23, 24, 25)	1.0
$D5$	(16.5, 19, 21.5)	0.7	$D5$	(14.5, 15, 15.5)	0.9	$D5$	(20.5, 21, 21.5)	0.9
$D6$	(14, 17, 20)	1.0	$D6$	(12, 13, 14)	1.2	$D6$	(24, 25, 26)	1.2
$D7$	(13, 16, 19)	0.9	$D7$	(11, 12, 13)	1.1	$D7$	(23, 24, 25)	1.1
$D8$	(13, 16, 21)	0.6	$D8$	(11, 12, 13)	0.8	$D8$	(17, 18, 19)	0.8
$D9$	(13.5, 16, 18.5)	0.7	$D9$	(11.5, 12, 12.5)	0.9	$D9$	(17.5, 18, 18.5)	0.9
$D10$	(13.5, 15, 19.5)	0.9	$D10$	(11.5, 11, 11.5)	1.1	$D10$	(17.5, 18, 19.5)	1.1

Table 5: Solutions with different costs.

$C1$	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
	31.08	23.436	18.924	13.052	12.668
	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
	12.602	29.08	14.18	15.846	12.796
$C2$	x_{41}	x_{71}	x_{101}	x_{12}	x_{22}
	18.924	13.052	12.602	31.08	29.08
	x_{32}	x_{62}	x_{53}	x_{84}	x_{94}
	23.436	14.18	15.846	12.668	12.796
$C3$	x_{41}	x_{22}	x_{62}	x_{53}	x_{14}
	18.924	29.08	14.18	15.846	31.08
	x_{34}	x_{74}	x_{84}	x_{94}	x_{104}
	23.436	13.052	12.668	12.796	12.602

Table 6: Solutions with different percentage of rejected items.

$T1$	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
	31.08	23.436	18.924	13.052	12.668
	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
	12.602	29.08	14.18	15.846	12.796
$T2$	x_{41}	x_{71}	x_{22}	x_{62}	x_{53}
	18.924	13.052	29.08	14.18	15.846
	x_{34}	x_{84}	x_{94}	x_{104}	x_{15}
	23.436	12.668	12.796	12.602	31.08
$T3$	x_{23}	x_{53}	x_{63}	x_{14}	x_{34}
	29.08	15.846	14.18	31.08	23.436
	x_{44}	x_{74}	x_{84}	x_{94}	x_{104}
	18.924	13.052	12.668	12.796	12.602

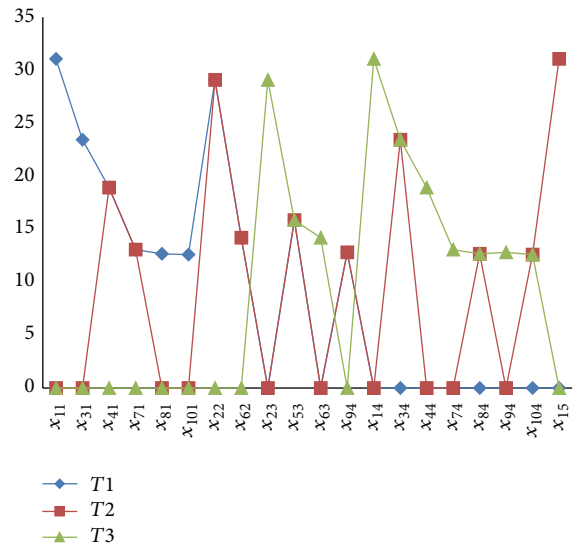

Figure 2: Solutions with different percentage of rejected items.

decision making with the common state since the risk of each supplier is unchanged to customers. When unique event occurs for some suppliers, however, the distribution of solutions altered which means that the customer leans to the suppliers with lower probability of risk situations.

In the following parts, we will discuss the relation between the expected value of total profits and the total loss of risk in our model. Generally, people extend the demand for item and the selling price or reduce the costs in order to achieve more profits. However, it is hard to control the variance of the selling price and costs of item, which are usually dominated by the fluctuation of market. It is reasonable and effective to adjust the parameters of demand. According to the MOP model and the analysis above, the value of solutions increases with the mean value of $\tilde{D}_i$ added, and the value of total loss of risk increases simultaneously. We list several groups of parameter $\tilde{D}_i$, the corresponding relation between the expected value of total profits and the total loss of risk shown in Figure 4 which indicates the loss of risk while achieving more profits.

According to the analysis and computation above, this random fuzzy MOP with risk objective model reminds the decision maker that more profits bring more risk. In addition, the model indicates that quantity purchased (x_{ij}) is impacted by both customer and supplier. The distribution of x_{ij}, which denotes the choosing of supplier from the customer, is affected by the costs (c_{ij}), the quality (τ_{ij}), the service (λ_{ij}), and the risk situations of different suppliers. The quantity (x_{ij}) is determined mostly by the demand of customers $\tilde{D}_i$.

Table 7: Solutions with different percentage of rejected items.

$P = 0.02$	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
$\pi_j = 0.05$	31.08	23.436	18.924	13.052	12.668
$L_{0j} = 50$	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
$(j = 1, 2, \ldots, 5)$	12.602	29.08	14.18	15.846	12.796
$P = 0.08$	x_{11}	x_{31}	x_{41}	x_{71}	x_{81}
$\pi_j = 0.05$	31.08	23.436	18.924	13.052	12.668
$L_{0j} = 60$	x_{101}	x_{22}	x_{62}	x_{53}	x_{94}
$(j = 1, 2, \ldots, 5)$	12.602	29.08	14.18	15.846	12.796
$P = 0.02, \pi_1 = 0.1$	x_{23}	x_{53}	x_{63}	x_{14}	x_{34}
$\pi_j = 0.05, j = 2, \ldots, 5$	29.08	15.846	14.18	31.08	23.436
$L_{01} = 60,$	x_{44}	x_{74}	x_{84}	x_{94}	x_{104}
$L_{0j} = 50, j = 2, \ldots, 5$	18.924	13.052	12.668	12.796	12.602

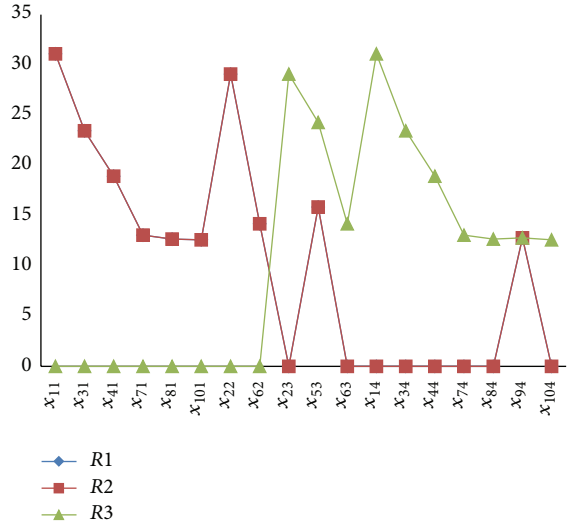

Figure 3: Solutions with different risk situations.

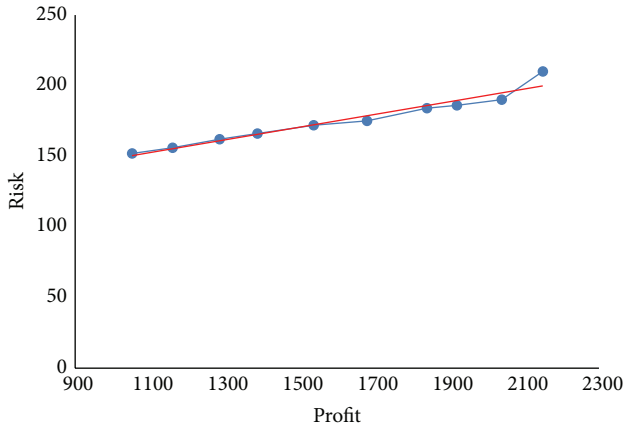

Figure 4: Relation between profits and risk.

5. Managerial Implications

Some implications about the contribution of our research to the supplier selection management and supply chain risk management are summarized as follows.

To consider catastrophic, "superevents," which affect many/all suppliers, and "unique events" that affect only a single supplier, effective forecast of the uncertainty and its possible impact on suppliers could help us make right supplier selection strategy. Furthermore, risk-averse ability could be taken as one of the important criteria for choosing the best suppliers.

In management practice, beyond traditional supplier selection system, by considering customer demand and unit purchase cost, we provide the decision maker with a simple tool for coordinating the flows of parts from suppliers to customers. The approach allows the managers to structure the distribution of cost or customer service level by selecting the optimal supply combination and scheduling of customer orders.

Application of the novel multiobjective programming with mixed uncertain coefficients could help the companies cope with the supply chain risk. The proposed model simultaneously maximizes the total profits and minimizes the percentage of items delivered late, percentage of items rejected, and the total loss cost due to supplier dysfunction.

6. Conclusion

Through analyzing three types of risk events in a supply chain system, (i) the superevents; (ii) when all suppliers close down during the supply cycle; and (iii) when some, but not all the suppliers, close down, we proposed a novel multiobjective programming with mixed uncertain coefficients developed for managing the supply chain risk. In this model, the customer demand is considered to be a random fuzzy variable and unit purchase cost is considered to be a fuzzy variable due to their uncertainty. According to the expected value and chance constraint operators, the uncertain model was converted into a deterministic one. By examining a numerical example, we found that (1) the confidence level and demand of customers have impact on the quantities purchased by customers from suppliers although the distribution of suppliers will not change; (2) the cost, the quality, and the service also influence the selection of suppliers; and (3) the superevents had little influence on the distribution of supplier selection; however, when unique event occurs, the distribution of supplier selection will change.

Some other uncertainty and risk types are not considered in the present study. It is of great importance to further examine this issue in future research.

Appendix

A. Proof of Theorems

Proof of Theorem 1. Since $\overline{D}_i(\theta)$ is a random variable with the mean $\widetilde{u}_i(\theta)$ and the variance σ_i^2, then $E[\tilde{\overline{D}}_i(\theta)] = \widetilde{u}_i(\theta)$ is a fuzzy variable. By the membership function $\mu_{\widetilde{u}_i(\theta)}(t)$ of $\widetilde{u}_i(\theta)$ and the definition of credibility measure, we have

$$\begin{aligned}
&\mathrm{Cr}\left\{\theta \mid E\left[\tilde{\overline{D}}_i(\theta)\right] \geq t\right\} \\
&= \begin{cases} 1, & t \leq {a_i}^D \\ 1 - \dfrac{1}{2}L\left(\dfrac{{b_i}^D - t}{{a_i}^D}\right), & {a_i}^D \leq t \leq {b_i}^D \\ \dfrac{1}{2}R\left(\dfrac{t - {b_i}^D}{{c_i}^D}\right), & {b_i}^D \leq t \leq {c_i}^D \\ 0, & t \geq {c_i}^D. \end{cases}
\end{aligned} \tag{A.1}$$

It follows, from the definition of the expected value operator of random fuzzy variables, that

$$\begin{aligned}
E\left[\tilde{\overline{D}}_i\right] &= \int_0^{+\infty} \mathrm{Cr}\left\{\theta \in \Theta \mid E\left[\tilde{\overline{D}}_i(\theta)\right] \geq t\right\} dt \\
&\quad - \int_{-\infty}^{0} \mathrm{Cr}\left\{\theta \in \Theta \mid E\left[\tilde{\overline{D}}_i(\theta)\right] \leq t\right\} dt \\
&= \int_0^{{a_i}^D} 1\, dt + \int_{{a_i}^D}^{{b_i}^D} \left[1 - \frac{1}{2}L\left(\frac{{b_i}^D - t}{{a_i}^D}\right)\right] dt \\
&\quad + \int_{{b_i}^D}^{{c_i}^D} \frac{1}{2}R\left(\frac{t - {b_i}^D}{{c_i}^D}\right) \\
&= {b_i}^D + \frac{{a_i}^D}{2}\left[F_L\left({b_i}^D\right) - F_L\left({a_i}^D\right)\right] \\
&\quad + \frac{{c_i}^D}{2}\left[F_R\left({b_i}^D\right) - F_R\left({c_i}^D\right)\right],
\end{aligned} \tag{A.2}$$

where $F_L(x)$ and $F_R(x)$ are continuous functions while $F_L'(x) = L(x)$, $x \in [{a_i}^D, {b_i}^D]$, $F_R'(x) = L(x)$, and $x \in [{b_i}^D, {c_i}^D]$. This completes the proof. □

Proof of Theorem 2. According to Dickson [17] and Håkansson and Snehota [18], we have that

$$\begin{aligned}
E\left(\widetilde{c}_{ij}\right) &= \int_0^{+\infty} \mathrm{Cr}\left\{\widetilde{c}_{ij} \geq r\right\} dr - \int_{-\infty}^{0} \mathrm{Cr}\left\{\widetilde{c}_{ij} \leq r\right\} dr \\
&= \frac{\left(a_{ij}^c + 2b_{ij}^c + c_{ij}^c\right)}{4}.
\end{aligned} \tag{A.3}$$

Input: Initial data and GA parameters
Output: Optimal solutions and objective values
Begin
  $t \leftarrow 1$;
  initialization $P(N_{\text{pop-size}})$ by feasibility check;
  fitness eval(P);
  while (*not termination condition*) **do**
    selection();
    crossover();
    mutation();
    evaluation(t)
    $t \leftarrow t + 1$;
  end
  Output: Optimal solutions and objective values
end

Pseudocode 1: Comprised solution-based GA.

For the risk objective $f_4(x_{ij})$, in which I_0 and I_j indicate random variable and lead the uncertainty, we use expected value operator of random variable in order to reduce the anticipative risk.

$$\begin{aligned}
&E\left[f_4\left(x_{ij}\right)\right] \\
&\quad = E\left\{\left[I_0 + \left(1 - I_0\right)\prod_{j=1}^{n_i} I_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right)\right\}.
\end{aligned} \tag{A.4}$$

From the preanalysis, we have

$$\begin{aligned}
P\left(I_0 = 1, I_j = 0\right) &= p\prod_{j=1}^{n_i}\left(1 - \pi_j\right), \\
P\left(I_0 = 0, I_j = 1\right) &= \left(1 - p\right)\prod_{j=1}^{n_i}\pi_j.
\end{aligned} \tag{A.5}$$

It follows that

$$\begin{aligned}
&E\left[f_4\left(x_{ij}\right)\right] \\
&\quad = p\prod_{j=1}^{n_i}\left(1 - \pi_j\right)\sum_{j=1}^{n_i}\left(L_0 x_{ij}\right) \\
&\qquad + \left(1 - p\right)\prod_{j=1}^{n_i}\pi_j\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right) \\
&\quad = \left[p\prod_{j=1}^{n_i}\left(1 - \pi_j\right) + \left(1 - p\right)\prod_{j=1}^{n_i}\pi_j\right]\sum_{j=1}^{n_i}\left(L_{0j}x_{ij}\right).
\end{aligned} \tag{A.6}$$

According to the chance constraint, we have that, for $0 \leq \alpha_i$, $\beta \leq 1$,

$$
\begin{aligned}
&\mathrm{Ch}\left\{\tilde{\overline{D}}_i \le \sum_{j=1}^{n_i} x_{ij}\right\}(\alpha_i) \ge \beta_i \Longleftrightarrow \\
&\mathrm{Pos}\left\{\theta \mid \mathrm{Pr}\left\{\overline{D}_i(\theta) \le \sum_{j=1}^{n_i} x_{ij}\right\} \ge \beta_i\right\} \ge \alpha_i \Longleftrightarrow \\
&\mathrm{Pos}\left\{\Phi\left(\frac{\sum_{j=1}^{n_i} x_{ij} - \widetilde{\mu}_i^D(\theta)}{\sigma}\right) \ge \beta_i\right\} \ge \alpha_i \Longleftrightarrow \\
&\mathrm{Pos}\left\{\theta \mid \widetilde{\mu}_i^D(\theta) \le \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta)\right\} \ge \alpha_i \Longleftrightarrow \\
&\alpha_i \le \begin{cases} 0, & \text{if } \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \le {a_i}^D \\ L\left(\dfrac{{b_i}^D - \left[\sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i)\right]}{{a_i}^D}\right), & \text{if } {a_i}^D \le \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \le {b_i}^D \\ 1, & \text{if } \sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \ge {b_i}^D \end{cases} \Longleftrightarrow \\
&\sum_{j=1}^{n_i} x_{ij} - \sigma\Phi^{-1}(\beta_i) \ge \max\left\{{a_i}^D, {b_i}^D - {a_i}^D L^{-1}(\alpha_i)\right\},
\end{aligned}
\tag{A.7}
$$

where Ch{·} denotes the chance of the random fuzzy event and possibility α_i and probability β_i are specified confidence levels. This completes the proof. □

B. Pseudo Codes

See Pseudocode 1.

Competing Interests

The authors declare that they have no competing interests.

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Research Article

Dependent-Chance Goal Programming for Water Resources Management under Uncertainty

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Without sufficient data, consulting experts is a good way to quantify unknown parameters in water resources management which will result in human uncertainty. The aim of this paper is to introduce a new tool-uncertainty theory to deal with such uncertainty which is treated as uncertain variable with uncertainty distribution. And a dependent-chance goal programming (DCGP) model is provided for water resources management under such circumstance. In the model uncertain measure is used to measure possibility that an event will occur which is maximized by minimizing the deviation (positive or negative deviation) from target of objective event under a given priority structure. In the end, the developed model is applied to a numerical example to illustrate the effectiveness of the model. The result obtained contributes to the desired water-allocation schemes for decision-markers.

1. Introduction

The water resources management aims to enhance the effective use and guarantee sustainable development of water resources, when requirements about water quality and quantity of users are satisfied. Generally, there are several essential principles for water resources management: maximize the benefits in the development and utilization of water resources; emphasize joint operation of surface water and groundwater; lay equal stress on development and protection of water resources; strike a balance between water quality and water quantity. However, some natural and human factors (extreme climate events, emergency, population growth, etc.) bring severe challenges for efficient management of water resources, such as severe water shortage and water pollution. Obviously, these challenges will intensify the uncertainty of water resources management. However, in earlier study, researchers seldom consider uncertainty which already exists in water resources management. For example, Howes [1] applied linear programming to obtain doable water resource investments for water development projects. Revelle et al. [2] minimized the cost of the treatment plants in water quality management by using linear programming approach. Howard and Shamir [3] established a deterministic linear programming model to study interrelated land and water resource management problem. These approaches above did not take indeterminate factors into consideration.

However, in reality, uncertainty often influences decision-making in water resources allocation, utilization, scheduling, and protection. Later, researchers noted and treated uncertainty as randomness, fuzziness, or both of them. As a result, numerous mathematical methods have been proposed based on stochastic programming to tackle uncertainty treated as randomness. For example, Dupačová et al. [4] utilized stochastic programming to offer alternative decisions for decision-makers in water management. Feiring et al. [5] proposed a stochastic programming model for agricultural irrigation where rainfall was assumed to be a random variable. Huang and Loucks [6] proposed an inexact two-stage stochastic programming model to deal with uncertainty where total water available and net benefit were unknown in water resources management. Kracman et al. [7] developed a multistage stochastic optimization model to handle uncertainty in the inflows into the Highland Lakes of the Highland Lakes system. Zhou et al. [8] proposed a factorial multistage stochastic programming approach for water resources management under uncertainty where some parameters of water allocation are indeterminate. Besides, some researchers used

fuzzy programming to handle uncertainty presented as fuzzy set. For example, Jairaj and Vedula [9] formulated a fuzzy mathematical programming model based on fuzzy set theory for a multireservoir system. Sahoo et al. [10] used fuzzy optimization and liner programming to optimize the allocation of land and water resources. Zhang et al. [11] proposed an interactive inexact fuzzy bounded programming approach for agricultural water quality management. Sometimes, multiple uncertainties also exist in water resources management problems. Recent years, some methods are addressed through combining different mathematical programming method to deal multiple uncertainties. Guo et al. [12] developed a fuzzy stochastic two-stage programming approach for water resources management under randomness and fuzziness which integrated the fuzzy robust programming, chance-constrained programming, and two-stage stochastic programming. Li et al. [13] proposed fuzzy-boundary interval-stochastic programming method to tackle uncertainties expressed as probability distributions and fuzzy-boundary intervals. Zeng et al. [14] developed a two-stage credibility-constrained programming with Hurwicz criterion approach to tackle uncertainties presented as probability distributions and fuzzy sets.

These existing methods are effective to deal with objective uncertainty based on probability theory and fuzzy set theory. However, human uncertainty also exists in water resources management. Without sufficient data, consulting experts is another choice to quantify unknown parameter. In this case, human uncertainty always occurs. It is a fact that probability theory is a useful tool when a large number of sample data exists. So it is less effective to tackle such problems based on probability theory if there is lack of sample data. Besides, some researchers used fuzzy set theory to deal with human uncertainty. But it does not emphasize the law of excluded middle and the law of contradiction. In contrast, uncertainty theory [15] follows these principles which was founded in 2007 and became a branch of mathematics based on the normality, duality, and countable subadditivity. It is noteworthy that uncertainty theory is a new mathematical tool rather than a general term for all theory to handle uncertainty. Nowadays, it has been applied to different fields to tackle with uncertain phenomenon. For example, Liu proposed uncertain programming [16], uncertain multiobjective programming and uncertain goal programming [17], and uncertain multilevel programming [18] to deal with decision processing including belief degree successively.

Compared with probability theory and fuzzy set theory, uncertainty theory is effective in handling human uncertainty. So based on uncertainty theory, this paper considers the optimal allocation of water supply systems in uncertain environment. And uncertainty is expressed as uncertain variable with uncertainty distribution. Then the uncertain measure is used to measure possibility that an event will occur. The objective function of this model is to minimize the deviation from target of objective event under a given priority structure. Thus, DCDP model is formulated.

The rest of this paper is organized as follows. Section 2 introduces some basic concepts of uncertainty theory used throughout this paper. Section 3 presents a dependent-chance goal programming model for the water supply system under uncertain environment. Section 4 introduces algorithm to solve the model. Section 5 gives a numerical example to illustrate the effectiveness of the model. Finally, a conclusion is drawn in Section 6.

2. Preliminaries

In this section, we will introduce some useful definitions about uncertain measure, uncertain distribution, and so on.

Let Γ be a nonempty set, and $\mathscr{L}$ be σ-algebra over Γ. Each element $\Lambda \in \mathscr{L}$ is called an event. A number $\mathscr{M}\{\Lambda\}$ indicates the possibility that Λ will occur. Uncertain measure $\mathscr{M}$ is introduced as a set function satisfying the following axioms [15]:

Axiom 1 (normality axiom). $\mathscr{M}\{\Gamma\} = 1$ for the universal set Γ.

Axiom 2 (duality axiom). $\mathscr{M}\{\Lambda\} + \mathscr{M}\{\Lambda^c\} = 1$ for any event Λ.

Axiom 3 (subadditivity axiom). For every countable sequence of events $\{\Lambda_i\}$, we have

$$\mathscr{M}\left\{\bigcup_{i=1}^{\infty}\Lambda_i\right\} \leq \sum_{i=1}^{\infty}\mathscr{M}\left\{\Lambda_i\right\}. \tag{1}$$

The triplet $(\Gamma, \mathscr{L}, \mathscr{M})$ is called an uncertainty space. In addition, the product uncertain measure [19] was defined as follows.

Axiom 4 (product axiom). Let $(\Gamma_k, \mathscr{L}_k, \mathscr{M}_k)$ be uncertainty spaces for $k = 1, 2, \ldots$. The product uncertain measure $\mathscr{M}$ is an uncertain measure satisfying

$$\mathscr{M}\left\{\prod_{k=1}^{\infty}\Lambda_k\right\} = \bigwedge_{k=1}^{\infty}\mathscr{M}_k\left\{\Lambda_k\right\}. \tag{2}$$

The concept of uncertain variable ξ was introduced [15] as a measurable function from an uncertainty space $(\Gamma, \mathscr{L}, \mathscr{M})$ to the set of real numbers. In order to describe an uncertain variable, uncertainty distribution is defined [15] as

$$\Phi(x) = \mathscr{M}\left\{\xi \leq x\right\}, \quad \forall x \in \mathfrak{R}. \tag{3}$$

Furthermore, the inverse uncertain distribution $\Phi^{-1}(\alpha)$ of ξ was defined [20]. It plays a crucial role in operations of uncertain variable.

An uncertain variable ξ is called normal if it has a normal uncertainty distribution [15]

$$\Phi(x) = \left(1 + \exp\left(\frac{\pi(e - x)}{\sqrt{3}\sigma}\right)\right)^{-1}, \quad x \in R, \tag{4}$$

denoted by $N(e, \sigma)$, where e and σ are real numbers with $\sigma > 0$.

An uncertain variable ξ is called lognormal if it has a normal uncertainty distribution [15]

$$\Phi(x) = \left(1 + \exp\left(\frac{\pi(e - \ln x)}{\sqrt{3}\sigma}\right)\right)^{-1}, \quad x \geq 0, \tag{5}$$

denoted by LOGN(e, σ), where e and σ are real numbers with $\sigma > 0$.

3. DCGP Model under Uncertainty Environments

Usually, optimal allocation of water supply system is a multiobjective programming problem. However, these goals are often contradictory and achievable at the cost of other goals. In this case, it is a preferred solution to create a priority structure. Then the lower-priority goals are considered after achieving the higher-priority goals. Under such circumstances, based on probability theory, dependent-chance goal programming (DCGP) [21] was firstly proposed to deal with the complex system which contains multiple resources and multiple users. Later the former one was improved and applicable for general stochastic decision systems [22], fuzzy decision systems [23], and fuzzy random systems [24]. Specifically, DCGP is a good tool to deal with water supply-allocation problem, production process [25], capital budgeting [26], and so on.

However, it is reasonable to accept the existence of the system (or phenomenon) which is neither random nor fuzzy. The phenomenon that there is lack of sufficient historical data is a case. In order to cope with such decision systems, uncertainty theory is used to formulate DCGP as follows:

$$\begin{aligned} \min \quad & \sum_{j=1}^{l} P_j \sum_{i=1}^{m} \left(u_{ij} d_i^+ + v_{ij} d_i^- \right) \\ \text{subject to:} \quad & M \left\{ \begin{matrix} h_{ik}(\mathbf{x}, \boldsymbol{\xi}) \le 0 \\ k = 1, 2, \ldots, q_i \end{matrix} \right\} + d_i^- - d_i^+ = b_i, \\ & \qquad i = 1, 2, \ldots, m, \\ & g_j(\mathbf{x}, \boldsymbol{\xi}) \le 0, \quad j = 1, 2, \ldots, p, \\ & d_i^+, d_i^- \ge 0, \quad i = 1, 2, \ldots, m, \end{aligned} \tag{6}$$

where some parameters are shown as follows: P_j is the priority factor which represents the relative importance of each goal; l is number of priorities; u_{ij} is the weighting factor of positive deviation for goal i under priority j assigned; v_{ij} is the weighting factor of negative deviation for goal i under priority j assigned; m is the number of goal constraints; b_i is given target value of goal i.

The objective event is expressed as $h_{ik}(\mathbf{x}, \boldsymbol{\xi}) \le 0$, $k = 1, 2, \ldots, q_i$, $i = 1, 2, \ldots, m$, where $\mathbf{x}$ is decision vector and $\boldsymbol{\xi}$ is uncertain vector. $M\{h_{ik}(\mathbf{x}, \boldsymbol{\xi}) \le 0,\ k = 1, 2, \ldots, q_i,\ i = 1, 2, \ldots, m\}$ is uncertain measure of event occurrence. Let $f_i(\mathbf{x})$ be the chance function of the objective event

$$f_i(\mathbf{x}) = \left\{ \begin{matrix} M\left\{ h_{ik}(\mathbf{x}, \boldsymbol{\xi}) \le 0 \right\},\ k = 1, 2, \ldots, q_i \\ g_j(\mathbf{x}, \boldsymbol{\xi}) \le 0,\ j \in J_i \end{matrix} \right\}, \tag{7}$$

where J_i is the dependant constraints of objective event i ($i = 1, 2, \ldots, m$).

On the basis of chance functions and goal values, the deviations (positive or negative deviations) can be defined.

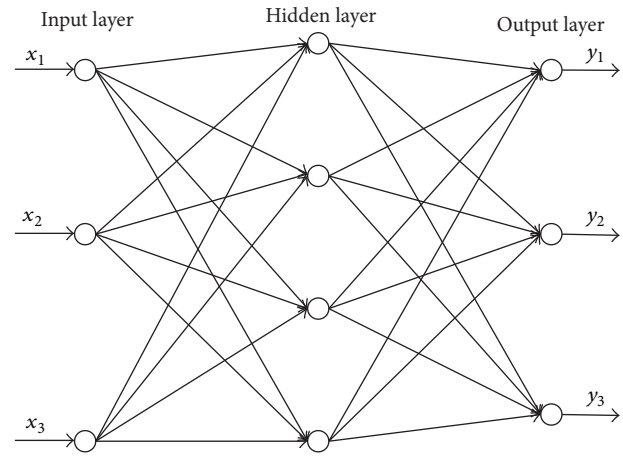

Figure 1: BP neural network structure.

Let d_i^+ be the positive deviation from the target of goal i, denoted as

$$d_i^+ = \begin{cases} f_i(\mathbf{x}) - b_i, & f_i(\mathbf{x}) > b_i, \\ 0, & f_i(\mathbf{x}) \le b_i,\ i = 1, 2, \ldots, m. \end{cases} \tag{8}$$

Let d_i^- be the negative deviation from the target of goal i, denoted as

$$d_i^- = \begin{cases} 0, & f_i(\mathbf{x}) \ge b_i, \\ b_i - f_i(\mathbf{x}), & f_i(\mathbf{x}) < b_i,\ i = 1, 2, \ldots, m. \end{cases} \tag{9}$$

The constraints $g_j(\mathbf{x}, \boldsymbol{\xi}) \le 0$, $j = 1, 2, \ldots, p$, are the uncertain environment.

4. Hybrid Intelligent Algorithm

The hybrid intelligent algorithm which integrates uncertain simulation, neural network, and genetic algorithm is introduced to solve the model. The algorithm combines the global searching ability of genetic algorithm and the good local searching ability of neural network and improves training effect of neural network by using uncertain simulation.

To be more specific, the aim of uncertain simulation is to generate large amounts of input-output data. And neural network attempts to seek suitable weighting vector to approximate the uncertain functions by training input-output data (general network structure is shown in Figure 1). Finally, the optimum solution is obtained by applying genetic algorithm.

In conclusion, the concrete step of algorithm is just as follows (the framework of hybrid intelligent algorithm is shown in Figure 2).

Step 1. Apply uncertain simulation to generate input-output data for following uncertain functions; the number of simulations is T every time through the loop:

$$\begin{aligned} U : x \longrightarrow M \left\{ h_k(\mathbf{x}, \boldsymbol{\xi}) \le 0,\ k = 1, 2, \ldots, q;\ g_j(\mathbf{x}, \boldsymbol{\xi}) \right. \\ \left. \le 0,\ j \in J \right\}. \end{aligned} \tag{10}$$

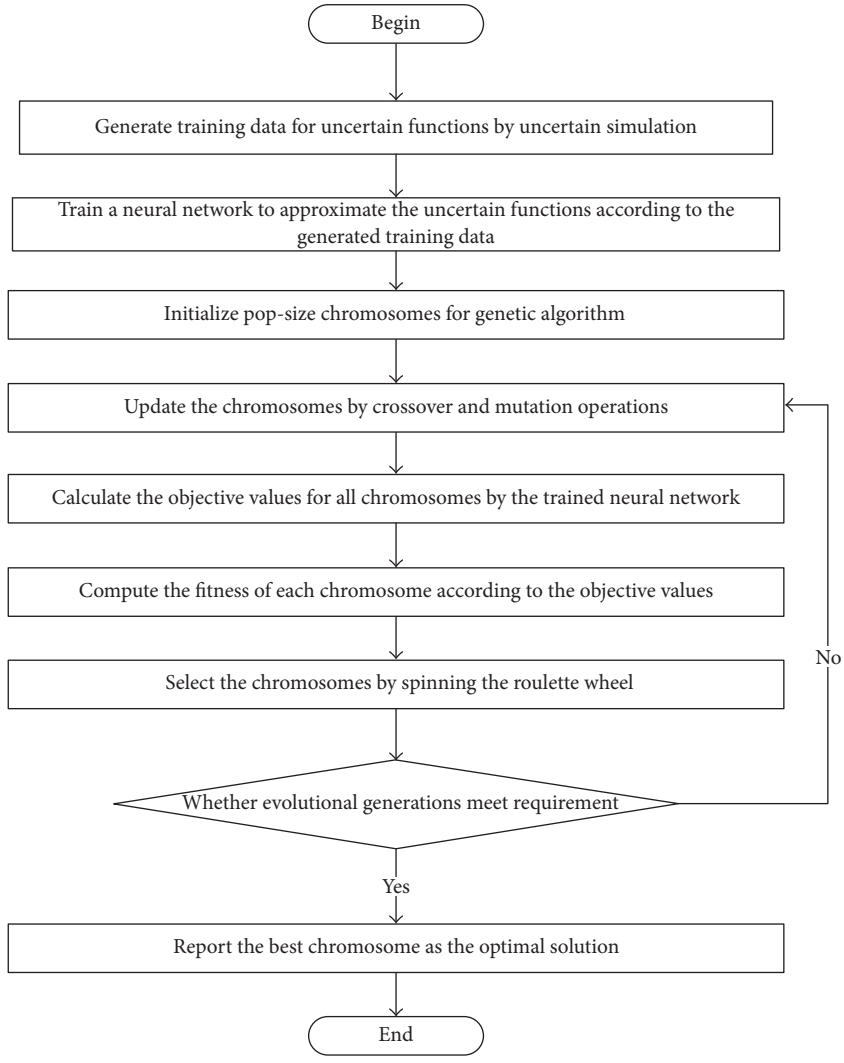

Figure 2: Framework of hybrid intelligent algorithm.

Step 2. Train a neural network according to input-output data generated by uncertain simulation. The error between training output and training data is minimized to approximate the uncertain functions. Finish train until training results are satisfying.

Step 3. Generate initial pop-size chromosomes randomly and check the feasibility of the chromosomes.

Step 4. Update the chromosomes by crossover and mutation operations.

Step 5. Calculate the objective values for all chromosomes by the trained neural network.

Step 6. Calculate the fitness of each chromosome in accordance with the objectives values by evaluation function.

Step 7. Choose the chromosomes by spinning the roulette wheel to create new chromosomes.

Step 8. Repeat Steps 4–7 until the number of cycles required.

Step 9. Select the best chromosome as the optimal solution of the model.

5. Application in Water Resources Management

In this section, let us consider a water supply and allocation problem shown in Figure 3. There are three newly constructed reservoirs for emergency water supply and three water users which are urban domestic, industrial, and agricultural sectors. In order to realize the demand of users, several problems need to be solved. Firstly, we need to consider the water quantity supplied by each reservoir. Secondly, the decisions to optimize the allocation of water resources should be made.

In order to solve above problems, we introduce 9 decision variables. x_1, x_2, and x_3 are quantities supplied from reservoir 1 to user $1, 2, 3$, respectively; x_4, x_5, and x_6 are quantities

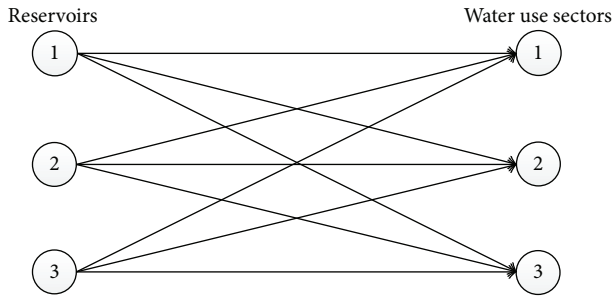

Figure 3: Water supply system.

supplied from reservoir 2 to user 1, 2, 3, respectively; x_7, x_8, and x_9 are quantities supplied from reservoir 3 to user 1, 2, 3, respectively. Remarkably, the water quantity supplied by each reservoir cannot exceed its maximum storage capacity which are marked by ξ_1, ξ_2, ξ_3. However, it is a challenge to quantify the maximum quantity without data about newly constructed reservoir. So let ξ_1, ξ_2, ξ_3 be independent uncertain variables with uncertainty distributions Φ_1, Φ_2, Φ_3, respectively. Then the constraint are as follows:

$$\begin{aligned} x_1 + x_2 + x_3 &\le \xi_1, \\ x_4 + x_5 + x_6 &\le \xi_2, \\ x_7 + x_8 + x_9 &\le \xi_3. \end{aligned} \tag{11}$$

At the same time, the demands of three users must be satisfied, marked by c_1, c_2, c_3. Then three are three events

$$\begin{aligned} x_1 + x_4 + x_7 &= c_1; \\ x_2 + x_5 + x_8 &= c_2; \\ x_3 + x_6 + x_9 &= c_3. \end{aligned} \tag{12}$$

Since emergencies happen, three newly constructed reservoirs are adoptable for emergency water supply and may not satisfied for all users. In this case, priority structure of three water sectors is supposed as follows.

Priority 1. The water supply rate in urban domestic reaches the given goal b_1 as much as possible.

Priority 2. The water supply rate in industry reaches the given goal b_2 as much as possible.

Priority 3. The water supply rate in agriculture reaches the given goal b_3 as much as possible.

Then the DCGP model is formulated:

$$\begin{aligned} \text{lexmin} \quad & \{d_1^-, d_2^-, d_3^-\} \\ \text{subject to:} \quad & M\{x_1 + x_4 + x_7 = c_1\} + d_1^- - d_1^+ = b_1 \\ & M\{x_2 + x_5 + x_8 = c_2\} + d_2^- - d_2^+ = b_2 \\ & M\{x_3 + x_6 + x_9 = c_3\} + d_3^- - d_3^+ = b_3 \\ & x_1 + x_2 + x_3 \le \xi_1 \\ & x_4 + x_5 + x_6 \le \xi_2 \\ & x_7 + x_8 + x_9 \le \xi_3 \\ & x_i \ge 0, \quad i = 1, 2, \ldots, 9 \\ & d_i^-, d_i^+ \ge 0, \quad i = 1, 2, 3. \end{aligned} \tag{13}$$

Now, suppose that the maximum quantities ξ_1, ξ_2, ξ_3 are uncertain variables with uncertainty distributions LOGN(2.2, 0.5), LOGN(1.1, 0.1), and LOGN(1.2, 0.3), respectively. The water demands of three users c_1, c_2, and c_3 are 2, 3, and 1, respectively. And the given goals b_1, b_2, and b_3 are 0.95, 0.90, and 0.85, respectively.

The hybrid intelligent algorithm is used to solve this model. And the values of each parameter are shown in Table 1.

A run of the hybrid intelligent algorithm shows that the optimal solution is

$$x = (1.0805, 1.4490, 0.1755, 0.1871, 0.5351, 0.4300, 0.7324, 1.0159, 0.3945)\,. \tag{14}$$

So, the optimal scheme is

quantities supplied from reservoir 1 to user 1, 2, 3 are 1.0805, 1.4490, 0.1755;

quantities supplied from reservoir 2 to user 1, 2, 3 are 0.1871, 0.5351, 0.4300;

quantities supplied from reservoir 3 to user 1, 2, 3 are 0.7324, 1.0159, 0.3945.

The result shows that quantities supplied by three newly constructed reservoirs meet the demand of users. So, decision-makers can set higher goals and make water supply plans according to obtained result.

In reality, multiple objectives are usually in conflict and can not be achieved simultaneously in water supply-allocation problem. In order to realize the global optimization, it is an alternative approach for decision-makers to create a priority structure and set values for these goals according to their contribution to decision-making. Thus it not only gives consideration to all goals at the same time but also assures the achievement of the higher-priority goals as much as possible.

Table 1: Value of each parameter.

Number of loops	T	6000
Input-output data	D	3000
Number of input neurons	N	6
Number of hidden neurons	H	15
Number of output neurons	O	3
Population size	Pop-size	30
Parameter of evaluation function	a	0.5
Crossover probability	P_c	0.3
Mutation probability	P_m	0.2
Number of iterations	Gen	1000

6. Conclusions

This study proposes a dependent-chance goal programming model under uncertain environment in the absence of historical data as reference. Different from previous dependent-chance goal programming under random and environment, the uncertain variable and uncertain measure are brought into the model based on uncertainty theory. In the model, possibility of an event's occurrence is measured by uncertain measure. The objective is to maximize the chance of an event's occurrence by means of minimizing the deviation (positive or negative deviation) from target of objective event under a given priority structure. Finally, an example is successfully solved to demonstrate the validity of the proposed model.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

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Research Article

3Es System Optimization under Uncertainty Using Hybrid Intelligent Algorithm: A Fuzzy Chance-Constrained Programming Model

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Harmonious development of 3Es (economy-energy-environment) system is the key to realize regional sustainable development. The structure and components of 3Es system are analyzed. Based on the analysis of causality diagram, GDP and industrial structure are selected as the target parameters of economy subsystem, energy consumption intensity is selected as the target parameter of energy subsystem, and the emissions of COD, ammonia nitrogen, SO_2, and NO_X and CO_2 emission intensity are selected as the target parameters of environment system. Fixed assets investment of three industries, total energy consumption, and investment in environmental pollution control are selected as the decision variables. By regarding the parameters of 3Es system optimization as fuzzy numbers, a fuzzy chance-constrained goal programming (FCCGP) model is constructed, and a hybrid intelligent algorithm including fuzzy simulation and genetic algorithm is proposed for solving it. The results of empirical analysis on Shandong province of China show that the FCCGP model can reflect the inherent relationship and evolution law of 3Es system and provide the effective decision-making support for 3Es system optimization.

1. Introduction

How to balance the economic development, energy security, and environmental protection to achieve sustainable development has been one of the greatest challenges of the 21st century. Referred to as the 3Es (economy-energy-environment) issues, they often involve simultaneous consideration of the speed and quality of economic development, energy consumption, and pollutants and GHGs (greenhouse gases) emissions. Therefore, it is imperative to optimize 3Es system in order to achieve coordinated development. The coordination is not only the basic assurance for the energy security and sustainable development of economy, but also an effective way to reduce environmental pollution.

There are some researches on the optimization of 3Es system, and a number of optimization models have been proposed. According to the modelling method, 3Es models can be divided into three categories, that is, top-down model, bottom-up model, and mixed model [1]. CGE (computable general equilibrium) model is a representative top-down model, which takes economic model as the core technology, and focuses on the interactions between energy price, economic elasticity, energy consumption, and energy production [2–4]. MARKAL (market allocation model), EFOM (energy flow optimization model), and LEAP (long range energy alternatives planning model) are widely used bottom-up models, and they apply optimization and simulation to predict and optimize the elements of 3Es. The most representative mixed models are NEMS (national energy modelling systems) and IIASA-WEC 3Es (IIASA-WEC energy-economic-environment model), and they optimize the whole 3Es system through emulation and simulation. Because top-down models do not have to describe energy and environmental technologies in detail, many researchers constructed top-down models. Zhang and Li constructed TH-3EM (Tsinghua hybrid energy-economy-environment assessment model) [5], which consist of CSCGEM, IESOM, and SICGE and other modules. Zhang et al. applied IESOM to simulate energy consumptions, energy structures, and carbon emissions in the different condition of emission mitigation

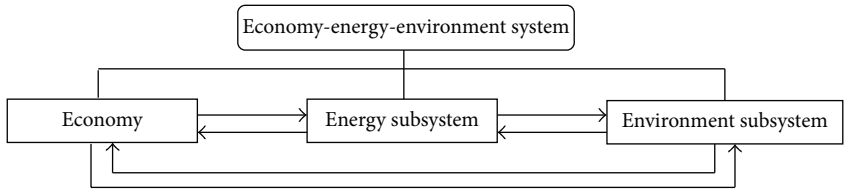

Figure 1: Elements and composition structure of 3Es system.

[6]. DeCarolis et al. applied ESOMs to uncover knife-edge solutions, explore alternative system configurations, and suggest different ways to achieve policy objectives under conditions of deep uncertainty [7]. Kambo et al. constructed a linear goal programming model for urban energy-economy-environment interaction [8], which used energy demand, energy conservation, air pollution, economic cost of energy system, energy imports, and utilization capacity as objectives and constraints. Oliveira and Antunes constructed a multiple objective model of 3Es interactions based on the linear input-output structure of interindustry [9]. Wei et al. applied the historical statistical data of Beijing city to construct a multiobjective goal programming model for Beijing's coordinated development of population, resources, environment, and economy [10]. Hu et al. put forward an economy-energy-electricity-environment framework and summarized the energy usage management and integrated resource strategic planning of China [11]. The above models are all the deterministic programming models with real number coefficients. Actually, because of the uncertainty of system evolution and forecast, it is better to see the parameters of 3Es system model as uncertain parameters. Liu et al. constructed a chance-constrained mixed-integer linear programming model with hybrid interval parameters for nonrenewable energy resources management under uncertainty, with an objective of maximizing economic return under constraints of resources availability and environmental regulations [12]. Cai et al. developed an interactive decision support system based on an interval parameter linear programming model to aid decision makers in planning energy management systems [13]. Fragnière and Haurie constructed a MARKAL model of Geneva [14], which regarded different policy scenes as a random event with some kind of possibility distribution, and carried out energy planning by random decision tree technology. Lin and Huang developed an interval parameter two-stage stochastic municipal planning model for supporting decisions of energy systems planning and GHG emission management at a municipal level [15]. Borges and Antunes considered the right side of input-output model as triangular fuzzy numbers and constructed a fuzzy multiple objective decision support model for energy-economy planning [16]. Weber and Martinsen constructed an energy system optimization model based on a fuzzy linear program and achieved an optimal compromise between system sustainability and cost minimization [17]. Zhang et al. adopted the fuzzy integral methods to offer an effective decision support for sustainable energy planning of Nanjing city [18].

In summary, 3Es system optimization is one of the significant ways to achieve the regional sustainable development. Extensive mathematical programming models have been put forward to demonstrate the relationships of 3Es system and obtain the optimal decision scheme. From the perspective of reality, uncertain models including interval, stochastic, and fuzzy programming models are better than deterministic models. Since plenty of statistical data is needed in the stochastic programming model to determine the probability distributions of variables, it is rarely used for 3Es optimization directly. Many interval and fuzzy programming models were constructed and applied for micro energy systems optimization, which were transformed into deterministic models with interaction parameters. Few studies constructed specifically the uncertain models of regional 3Es system considering targets of economy, energy, and environment subsystems simultaneously. In this paper, a fuzzy chance-constrained goal programming model (FCCGP) and its hybrid intelligent algorithm are put forward for optimization of 3Es system, and an empirical analysis on Shandong province is conducted for application of the above model and algorithm.

This paper is organized as follows: Section 2 analyzes the structure and components of 3Es system, selects the target parameters and decision variables, and constructs a FCCGP model for optimization of 3Es system. Section 3 provides a hybrid intelligent algorithm for solving the fuzzy model. Section 4 gives an empirical analysis on 3Es system optimization of Shandong province to testify the feasibility and validity of the FCCGP model and hybrid intelligent algorithm. Conclusions are presented in the last section.

2. FCCGP Model for Optimization of 3Es System

2.1. Economy-Energy-Environment System Analysis. 3Es system consists of three subsystems, namely, energy subsystem, economy subsystem, and environment subsystem, which interrelate with and influence each other. The development of each subsystem not only depends on its own structure but also depends on the other subsystems. The elements and composition structure of 3Es system are shown in Figure 1. Energy subsystem is the driving force of economy development and provides the power sources for the economic subsystem. Once the energy supply is threatened and unreliable, it will directly affect the economic output and even lead to economic recession. Meanwhile, economic subsystem plays important positive roles on the energy subsystem: firstly, economic development stimulates energy demand

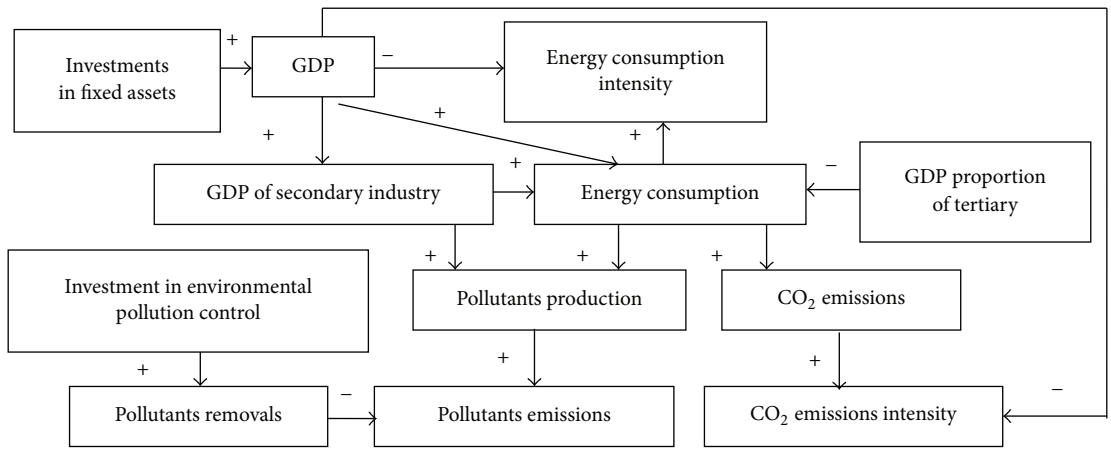

Figure 2: Causality diagram of 3Es system in Shandong province.

and provides the development space for energy subsystem; secondly, economic growth provides the material foundation of human, material, and financial resources for the development of energy subsystem; thirdly, economic growth drives the technological investment and progress in energy subsystem and consequently promotes the development of energy subsystem. Energy subsystem and environmental subsystem both conflict and coordinate with each other. The excessive exploitation and utilization of the energy subsystem can aggravate the environmental bearing capacity, and the degradation and destruction of the environment subsystem will make energy subsystem lose the foundation of exploitation. The development of economic subsystem, especially the industrial parts, accompanied by waste water, waste gas, solid waste, and GHGs, will cause environmental pollution, do harm to human health, and hinder the economic development.

Due to the fact that the impact value of energy investment and environmental pollution on the economic output is difficult to be estimated, the backward effects from energy of environment subsystem to economy subsystem are generally not considered into 3Es system optimization models. Referring to the literatures [8–10] and provincial development plan of China, the typical indicators are selected to construct the causality diagram shown in Figure 2. The main causal relationships are as follows:

(1) Investments in fixed assets → + GDP → + energy consumption → + CO_2 emissions → + CO_2 emissions intensity.

(2) GDP → + GDP of secondary industry → + pollutants production → + pollutants emissions.

(3) GDP proportion of tertiary → − energy consumption → + energy consumption intensity.

(4) Investment in environmental pollution control → + pollutants removals → − pollutants emissions.

2.2. Selection of Target Parameters and Decision Variables. Each subsystem of 3Es system has the corresponding targets. Generally, economy subsystem pursues high GDP growth rate and scientific industrial structure. GDP and three industry structures are selected as the target parameters of economic subsystem:

$$G_t = G_0 (1 + d)^t , \tag{1}$$

where G_0 and G_t are the GDP of the basic year and the target year and d is the average annual GDP growth rate.

Energy subsystem pursues lower growth rate of energy consumption and lower energy consumption intensity. Based on the target reduction ratio, the energy consumption intensity of the target year can be obtained by

$$e_t = e_0 (1 - r) , \tag{2}$$

where e_0 and e_t are the energy consumption intensities of the basic year and the target year and r is the reduction ratio of energy consumption intensity.

Environment subsystem pursues fewer emissions of pollutants and GHGs. The pollutants and GHGs usually include chemical oxygen demand (COD), ammonia nitrogen, sulphur dioxide (SO_2), nitrogen oxides (NO_X), and carbon dioxide (CO_2). Based on the reduction ratios, they can be computed by the following formula:

$$\begin{aligned} D_t &= D_0 (1 - r_D) , \\ A_t &= A_0 (1 - r_A) , \\ S_t &= S_0 (1 - r_S) , \\ N_t &= N_0 (1 - r_N) , \\ C_t &= C_0 (1 - r_C) , \end{aligned} \tag{3}$$

where D_0, A_0, S_0, and N_0 are the emissions of COD, ammonia nitrogen, SO_2, and NO_X of the basic year, D_t, A_t, S_t, and N_t are the emissions of the target year, C_0 and C_t are carbon emission intensities of the basic year and the target year, and r_D, r_A, r_S, r_N, and r_C are the reduction ratios of the above pollutants and CO_2.

According to the principles of controllability and exogenesis, the decision variables of the 3Es system include the investments in fixed assets of the three industries, total energy consumption, and total investment in environmental pollution control.

2.3. Formulation of FCCGP Model. 3Es system is a complex system and contains multiple optimization objectives. Generally, the target of economy subsystem includes two aspects: GDP of the target year is not lower than the planning value; industrial structure achieves the planning target; that is, the GDP proportions of primary industry and secondary industry are not higher than their target values and that of tertiary industry is not lower than its target value. The target of energy subsystem is that the energy consumption intensity is not higher than the planning value. The target of environment subsystem includes two aspects: the emissions of pollutants including COD, ammonia nitrogen, SO_2, and NO_X are not higher than their planning values; CO_2 emissions intensity is not higher than its planning value.

Due to the small sample of historical data and the uncertainty of forecasting, many parameters of 3Es system can be seen as fuzzy parameters. In this paper, a fuzzy chance-constrained goal programming model (FCCGP) is constructed for optimizing 3Es system. According to the above targets of 3Es system, the constraints consist of two types: (a) the uncertain constraint that each subsystem achieves its targets holding with a certain confidence level; (b) technical constraints. The uncertain constraints are as follows.

(1) GDP of the target year equals the sum of the added values of three industries:

$$G = \sum_{i=1}^{3} \left(I_i \times x_i\right), \tag{4}$$

where G is GDP of the target year, x_i is the fixed assets investment in the ith industry, I_i is the added value of unit investment in the ith industry, and I_i are fuzzy variables, $i = 1, 2, 3$.

(2) The fuzzy chance constraints that three industry structures of the target year should achieve the desired structure are satisfied with certain confidence levels:

$$\begin{aligned} &\mathrm{Cr}\left\{\frac{I_1 \times x_1}{G} - g_1 \le d_1^+\right\} \ge \alpha_1, \\ &\mathrm{Cr}\left\{\frac{I_2 \times x_2}{G} - g_2 \le d_2^+\right\} \ge \alpha_2, \\ &\mathrm{Cr}\left\{g_3 - \frac{I_3 \times x_3}{G} \le d_3^-\right\} \ge \alpha_3, \end{aligned} \tag{5}$$

where $\mathrm{Cr}\{A\}$ express the credibility that fuzzy event A occurs, g_i is the target value of GDP proportion of the ith industry, and α_i are the predetermined confidence levels by the decision-maker, $i = 1, 2, 3$.

(3) The constraint that GDP of the target year is not lower than the planning value is satisfied with a certain confidence level:

$$\mathrm{Cr}\left\{G_t - G \le d_4^-\right\} \ge \alpha_4, \tag{6}$$

where G_t is the target value of GDP and α_4 is the predetermined confidence level.

(4) The constraint that energy consumption intensity of the target year is not higher than the planning value is satisfied with a certain confidence level:

$$\mathrm{Cr}\left\{\frac{x_4}{G} - e \le d_5^+\right\} \ge \beta, \tag{7}$$

where x_4 is total energy consumption, e is the target value of energy consumption intensity, and β is the predetermined confidence level.

(5) The constraints that the emissions of COD, ammonia nitrogen, SO_2, NO_X, and CO_2 are not higher than their planning values are satisfied with certain confidence levels:

$$\begin{aligned} &\mathrm{Cr}\left\{P_1 \times I_2 \times x_2 - E_1 \times x_5 - D \le d_6^+\right\} \ge \gamma_1, \\ &\mathrm{Cr}\left\{P_2 \times I_2 \times x_2 - E_2 \times x_5 - A \le d_7^+\right\} \ge \gamma_2, \\ &\mathrm{Cr}\left\{P_3 \times I_2 \times x_2 - E_3 \times x_5 - S \le d_8^+\right\} \ge \gamma_3, \\ &\mathrm{Cr}\left\{P_4 \times I_2 \times x_2 - E_4 \times x_5 - N \le d_9^+\right\} \ge \gamma_4, \\ &\mathrm{Cr}\left\{\frac{c \times x_4}{G} - C \le d_{10}^+\right\} \ge \gamma_5, \end{aligned} \tag{8}$$

where x_5 is total investment in environmental pollution control, P_i are the production coefficients of COD, ammonia nitrogen, SO_2, and NO_X, that is, the productions of COD, ammonia nitrogen, SO_2, and NO_X per unit of the added value of secondary industry, $i = 1, 2, 3, 4$, respectively, E_i are the removal coefficients of COD, ammonia nitrogen, SO_2, and NO_X, that is, the removals of COD, ammonia nitrogen, SO_2, and NO_X per unit of investment in environmental pollution control, $i = 1, 2, 3, 4$, respectively, c is CO_2 emission coefficient, that is, CO_2 emissions per unit of energy consumption, D, A, S, and N are the target emissions of COD, ammonia nitrogen, SO_2, and NO_X, C is the target CO_2 emission intensity, P_i, E_i, and c are fuzzy variables, $i = 1, 2, 3, 4$, and $\gamma_1, \gamma_2, \ldots, \gamma_5$ are the predetermined confidence levels by the decision-maker.

The technical constraints include the following.

(1) Each decision variable should be within a certain range:

$$x_i^- \le x_i \le x_i^+, \quad i = 1, 2, \ldots, 5, \tag{9}$$

where x_i^- and x_i^+ are the lower limit and upper limit of the ith decision variable.

(2) The sum of investments in fixed assets of three industries should be within a certain range:

$$I^- \le \sum_{i=1}^{3} x_i \le I^+, \tag{10}$$

where I^- and I^+ are the lower limit and upper limit of the fixed assets investment of three industries.

(3) All the deviation variables are nonnegative:

$$d_1^+, d_2^+, d_3^-, d_4^-, d_5^+, d_6^+, d_7^+, d_8^+, d_9^+, d_{10}^+ \geq 0. \tag{11}$$

The objective of the model is to minimize the total deviations according to the priority structure and target levels set by the decision-maker:

$$\begin{aligned} \min \{ & P_{i_1} \left(w_1 d_1^+ + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^- \right), P_{i_2} d_5^+, \\ & P_{i_3} \left(u_1 d_6^+ + u_2 d_7^+ + u_3 d_8^+ + u_4 d_9^+ + u_5 d_{10}^+ \right) \}, \end{aligned} \tag{12}$$

where $P_{i_1}, P_{i_2}, P_{i_3}$ are the preemptive priority factors which express the relative importance of economy, energy, and environment targets, respectively. For example, if the priority order of them is economy $\succ$ energy $\succ$ environment, then $i_1 = 1$, $i_2 = 2$, $i_3 = 3$, and $P_1 \gg P_2 \gg P_3$. w_i and u_k are the weighting factors corresponding to the deviations of economy subsystem and environment subsystem, $i = 1, 2, 3, 4$, $k = 1, 2, \ldots, 5$, respectively, and they are all positive.

3. Solution Method of FCCGP Model

3.1. Fuzzy Simulation. Fuzzy simulation is a technology of sampling test for the fuzzy system model. If $\xi = f(\xi_1, \xi_2, \ldots, \xi_n)$ is a fuzzy vector defined on the credibility space $(\Theta, P(\Theta), \mathrm{Cr})$, α is predetermined confidence level, and the algorithm of fuzzy simulation for $\max\{\overline{f} \mid \mathrm{Cr}\{f(\mathbf{x}, \boldsymbol{\xi}) \geq \overline{f}\} \geq \alpha\}$ is as follows [19].

Step 1. Generate θ_k from Θ such that $\mathrm{Cr}\{\theta_k\} \geq \varepsilon/2$ ($k = 1, 2, \ldots, N$), where ε is a sufficiently small number.

Step 2. Find the maximal value r such that $L(r) \geq \alpha$ by employing bisection search method, where

$$\begin{aligned} L(r) = \frac{1}{2} \Bigg(& \max_{1 \leq k \leq N} \{ v_k \mid f(\mathbf{x}, \boldsymbol{\xi}(\theta_k)) \geq r \} \\ & + \min_{1 \leq k \leq N} \{ 1 - v_k \mid f(\mathbf{x}, \boldsymbol{\xi}(\theta_k)) < r \} \Bigg). \end{aligned} \tag{13}$$

Step 3. Return r as the estimation of $\overline{f}$.

3.2. Hybrid Intelligent Algorithm. A hybrid intelligent algorithm can be employed for solving the fuzzy chance-constrained goal programming model, which integrates fuzzy simulation and genetic algorithm. The procedure of this algorithm is as follows [20].

Step 1. Initialize a population with m chromosomes randomly, and the rth chromosome $\mathbf{x}^r = (x_1^r, x_2^r, \ldots, x_5^r)$ satisfies the constraints as follows:

$$\begin{aligned} & x_i^- \leq x_i^r \leq x_i^+, \quad i = 1, 2, \ldots, 5; \ r = 1, 2, \ldots, m, \\ & I^- \leq \sum_{i=1}^{3} x_i^r \leq I^+. \end{aligned} \tag{14}$$

Step 2. According to the credibility distributions of all the fuzzy variables including I_i, P_j, E_j, and c, $i = 1, 2, 3$, $j = 1, 2, 3, 4$, fuzzy simulation is applied to generate the data of uncertain functions $(e_1, e_2, \ldots, e_{10})$ like

$$\begin{aligned} e_1 &= \max \left\{ r_1 \mid \mathrm{Cr} \left\{ \frac{I_1 \times x_1}{G} \leq r_1 \right\} \geq \alpha_1 \right\}, \\ e_2 &= \max \left\{ r_2 \mid \mathrm{Cr} \left\{ \frac{I_2 \times x_2}{G} \leq r_2 \right\} \geq \alpha_2 \right\}, \\ e_3 &= \max \left\{ r_3 \mid \mathrm{Cr} \left\{ \frac{I_3 \times x_3}{G} \geq r_3 \right\} \geq \alpha_3 \right\}, \\ e_4 &= \max \left\{ \mathrm{Cr} \{ r_4 \mid G \geq r_4 \} \geq \alpha_4 \right\}, \\ e_5 &= \max \left\{ r_5 \mid \mathrm{Cr} \left\{ \frac{x_4}{G} \leq r_5 \right\} \geq \beta \right\}, \\ e_6 &= \max \{ r_6 \mid \mathrm{Cr} \{ P_1 \times I_2 \times x_2 - E_1 \times x_5 \leq r_6 \} \geq \gamma_1 \}, \\ e_7 &= \max \{ r_7 \mid \mathrm{Cr} \{ P_2 \times I_2 \times x_2 - E_2 \times x_5 \leq r_7 \} \geq \gamma_2 \}, \\ e_8 &= \max \{ r_8 \mid \mathrm{Cr} \{ P_3 \times I_2 \times x_2 - E_3 \times x_5 \leq r_8 \} \geq \gamma_3 \}, \\ e_9 &= \max \{ r_9 \mid \mathrm{Cr} \{ P_4 \times I_2 \times x_2 - E_4 \times x_5 \leq r_9 \} \geq \gamma_4 \}, \\ e_{10} &= \max \left\{ r_{10} \mid \mathrm{Cr} \left\{ \frac{c \times x_4}{G} \leq r_{10} \right\} \geq \gamma_5 \right\}. \end{aligned} \tag{15}$$

Step 3. Calculate the values of deviation variables of each chromosome: $d_1^+ = [e_1 - g_1] \vee 0$, $d_2^+ = [e_2 - g_2] \vee 0$, $d_3^- = [g_3 - e_3] \vee 0$, $d_4^- = [G_t - e_4] \vee 0$, $d_5^+ = [e_5 - e] \vee 0$, $d_6^+ = [e_6 - D] \vee 0$, $d_7^+ = [e_7 - A] \vee 0$, $d_8^+ = [e_8 - S] \vee 0$, $d_9^+ = [e_9 - N] \vee 0$, and $d_{10}^+ = [e_{10} - C] \vee 0$, and calculate their weighted sum

$$\begin{aligned} & P_{i_1} \left(w_1 d_1^+ + w_2 d_2^+ + w_3 d_3^- + w_4 d_4^- \right) + P_{i_2} d_5^+ \\ & \quad + P_{i_3} \left(u_1 d_6^+ + u_2 d_7^+ + u_3 d_8^+ + u_4 d_9^+ + u_5 d_{10}^+ \right) \end{aligned} \tag{16}$$

as the objective value.

Step 4. Compare all the objective values of m chromosomes, and rearrange them in descending order. Calculate the cumulative possibility of the sorted chromosome:

$$p_r = \sum_{t=1}^{r} a (1 - a)^{t-1}, \quad r = 1, 2, \ldots, m, \tag{17}$$

where a is the evaluation function parameter, $0 < a < 1$.

Step 5. Select chromosomes by spinning the roulette wheel; that is, repeat the following process m times: generating a random number p in $(0, p_m)$, the rth chromosome is selected if $p_{r-1} < p \leq p_r$. Output the new population $\mathbf{x}^f = (x_1^f, x_2^f, \ldots, x_5^f)$, $f = 1, 2, \ldots, m$.

Table 1: Data of the fixed assets investments, energy consumptions, and investment in environmental pollution control of Shandong province from 2000 to 2014.

Year	Fixed assets investment (10^8 Yuan)			Total energy consumption (10^4 tce)	Investment in environmental pollution control (10^8 Yuan)
	Primary industry	Secondary industry	Tertiary industry		
2000	77.1	1176.7	1288.8	11361.9	76.2
2001	78.2	1193.1	1306.9	9955.0	89.8
2002	79.1	1206.3	1321.3	14599.0	144.6
2003	81.4	1241.2	1359.6	16624.8	156.4
2004	87.4	1333.1	1460.2	19623.7	191.9
2005	89.9	1371.1	1501.8	24162.0	238.8
2006	91.5	1395.8	1528.8	26759.3	258.1
2007	95.2	1452.2	1590.6	29176.6	320.8
2008	102.5	1564.0	1713.1	30570.0	432.2
2009	99.4	1515.5	1660.0	32420.2	459.5
2010	103.0	1570.7	1720.4	34807.8	483.9
2011	110.0	1678.1	1838.1	37132.0	614.1
2012	110.9	1692.2	1853.5	38899.3	739.1
2013	111.4	1698.8	1860.7	35358.0	848.0
2014	111.7	1703.9	1866.3	36511.0	823.8

Sources: *Shandong Statistics Yearbook* 2001–2015 and *China Energy Statistical Yearbook* 2001–2015.
Note: — indicates the lack of data.

Step 6. Set a parameter p_j as the probability of crossover, and repeat the following process from $f = 1$ to m: generating a random number q from the interval $[0, 1]$, the chromosome $\mathbf{x}^f$ is selected as a parent if $q < p_j$. Make the linear crossover operation on the parent, and output the new population $\mathbf{x}^c = (x_1^c, x_2^c, \ldots, x_3^c)$, $c = 1, 2, \ldots, m$.

Step 7. Set a parameter p_b as the probability of mutation, and repeat the following process from $c = 1$ to m: generating a random number s from the interval $[0, 1]$, the chromosome $\mathbf{x}^c$ is selected as a parent if $s < p_b$. Make mutation operation on the parent, and output the new population $\mathbf{x}^b = (x_1^b, x_2^b, \ldots, x_5^b)$, $b = 1, 2, \ldots, m$, where all the chromosomes satisfy the constraints.

Step 8. Repeat the second to seventh steps for T cycles, and output the best chromosome as the optimal solution.

4. Empirical Analysis on Shandong Province

4.1. Data of Parameters. As a major economic province of China, Shandong province has achieved significant economic growth, and since 2007, its economic output has been ranked third in 31 provinces. Although many efforts have been made for energy saving and pollutants reduction, the energy efficiency level of Shandong province still falls behind the national average level [21, 22], and the major pollutants' emissions are still the largest. In this paper, empirical analysis is conducted on Shandong province, which provides the modelling process of the above FCCGP model and effective decision-making supports for its 3Es system optimization.

The data of the fixed assets investments of three industries at 2000 price index, total energy consumptions, and investment in environmental pollution control from 2000 to 2014 are shown in Table 1. All the indicators show the upward trend; therefore, regression, grey forecasting, and other forecasting methods can be used to forecast the future values theoretically.

The forecast of the fixed assets investment in primary industry is taken as an example to illustrate the application of various methods. Using the annual sequence number as independent variable, the linear regression (LR) equation of the fixed assets investment in primary industry can be obtained as follows:

$$FI_1 = 2.8271t + 72.6295$$
$$(60.7818)\ \ (21.5116) \tag{18}$$
$$R^2 = 0.9727,\ \ F = 426.7498,\ \ \text{sig.} = 1.51\text{e} - 11.$$

Note: data in the parentheses denote t-test values.

t-test and F value show that the regression equation is significant and can be used for short-term forecasting. Inputting $t = 16$ into the equation, the fixed assets investment in primary industry in 2015 is 117.9 billion Yuan.

By first-order accumulating operation on the raw data, the accumulated values of the fixed assets investment in primary industry can be represented as a row vector $X^{(1)} = \{77.1, 155.3, \ldots, 1428.7\}$, which satisfies the grey exponential law basically. According to grey forecasting (GF) theory, the albino equation can be written as follows:

$$\frac{dx^{(1)}}{d_t} + ax^{(1)} = b, \tag{19}$$

Table 2: Forecast results of decision variables in 2015.

Forecast method	Fixed assets investment (10^8 Yuan)			Total energy consumption (10^4 tce)	Investment in environmental pollution control (10^8 Yuan)
	Primary industry	Secondary industry	Tertiary industry		
LR	117.9	1797.7	1969.1	43613.5	851.2
GF	119.6	1824.8	1998.7	45597.1	1112.7
ER	120.2	1833.1	2008.0	51777.5	1211.8
PR	109.6	1672.5	1831.9	40551.8	735.2
QR	130.7	1778.8	1948.3	38334.4	984.6
CR	111.9	1707.3	1870.3	33948.2	970.3
Lower bound	109.6	1672.5	1831.9	33948.2	735.2
Upper bound	130.7	1833.1	2008.0	51777.5	1211.8

where a and b can be derived by using least squares estimation, and the calculation formulas are as follows:

$$\begin{bmatrix} a \\ b \end{bmatrix} = \left(B^T B\right)^{-1} B^T y_n,$$

$$B = \begin{bmatrix} -\frac{1}{2}\left(x_1^{(1)} + x_2^{(1)}\right) & 1 \\ -\frac{1}{2}\left(x_2^{(1)} + x_3^{(1)}\right) & 1 \\ \vdots & \vdots \\ -\frac{1}{2}\left(x_{n-1}^{(1)} + x_n^{(1)}\right) & 1 \end{bmatrix}, \quad (20)$$

$$y_n = \begin{bmatrix} x_2^{(0)} \\ x_3^{(0)} \\ \vdots \\ x_n^{(0)} \end{bmatrix}.$$

The results of a and b are −0.0295 and 75.6988, and the grey forecast model is

$$\begin{aligned} \widehat{x}_{t+1}^{(1)} &= \left(x_1^{(0)} - \frac{b}{a}\right) e^{-at} + \frac{b}{a} \\ &= 2641.9629 e^{0.0295t} + 75.6988. \end{aligned} \quad (21)$$

Because the above formula is the accumulated forecast model, regressive operation should be implemented for restoring the original value. Grey forecast results and actual values of the fixed assets investment in primary industry from 2000 to 2014 are shown in Figure 3.

The results of residual test and posterior variance test are as follows. The maximum relative error is 5.10%, the average relative error is 1.89%, the forecast accuracy is 98.11%, the posterior error ratio is 0.1945, and the small error frequency is 1. The test results show that grey forecast model has high precision and can be used for short-term forecasting. Inputting $t = 16$ into the model, the fixed assets investment of the first industry in 2015 is 119.6 billion Yuan.

In addition to the above forecasting methods, exponential regression (ER), power function regression (PR), quadratic regression (QR), and cubic curve regression (CR) can also be applied to fit the relation between the fixed assets investment in primary industry and the annual sequence number. The regression results are obtained as follows:

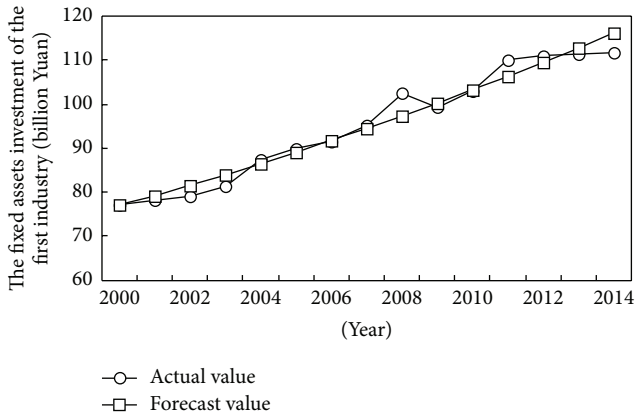

Figure 3: Comparison of grey forecast results and actual values.

$$\begin{aligned} &\text{ER: } FI_1 = 74.245 e^{0.0301t}, \quad R^2 = 0.9691, \\ &\text{PR: } FI_1 = 69.661 t^{0.1636}, \quad R^2 = 0.8773, \\ &\text{QR: } FI_1 = 0.0274t^2 + 3.2653t + 71.391, \\ &\qquad\qquad R^2 = 0.9736, \\ &\text{CR: } FI_1 = -0.0191t^3 + 0.4308t^2 + 0.2372t + 76.065, \\ &\qquad\qquad R^2 = 0.9827. \end{aligned} \quad (22)$$

All the correlation coefficient square values are greater than 0.8, so the above regression equations are significant. Inputting $t = 16$ into them, the forecast results are 120.2, 109.6, 130.7, and 111.9, respectively. Then the maximum and minimum values of the above results can be taken as the lower and upper bounds of the variable x_1 in 2015. In the same way, the forecast results of the other four decision variables in 2015 and their lower and upper bounds can be obtained as shown in Table 2.

The added values per unit investment of three industries from 2000 to 2014 are shown in Figure 4, and all three curves

Table 3: Forecast results of the added values per unit investment of three industries in 2015 (unit: Yuan/Yuan).

Forecast method	The added values per unit investment		
	Primary industry	Secondary industry	Tertiary industry
LR	20.57	14.77	7.48
GF	20.64	16.68	8.31
ER	20.66	17.31	8.37
PR	19.74	12.72	6.38
QR	20.80	15.83	8.14
CR	21.21	15.62	8.01

Table 4: The production coefficients of pollutants and CO_2 emission coefficients from 2000 to 2014.

Year	The production coefficients of pollutants ($t/10^8$ Yuan)				CO_2 emission coefficients ($t/10^4$ Yuan)
	COD	Ammonia nitrogen	SO_2	NO_X	
2000	531.08	—	427.73	—	1.5588
2001	473.72	13.63	383.51	—	1.5956
2002	385.00	12.52	340.54	—	1.2807
2003	338.53	10.41	339.03	—	1.5982
2004	280.36	9.58	293.57	—	1.6750
2005	247.16	9.03	284.08	—	2.2665
2006	199.37	13.91	311.22	121.74	2.0849
2007	180.69	7.29	251.87	89.25	1.9663
2008	182.83	8.00	280.38	77.03	1.9407
2009	165.39	9.27	273.67	73.96	1.7856
2010	154.63	11.32	268.44	69.16	1.6662
2011	150.94	7.00	314.13	68.12	1.5793
2012	134.31	5.69	239.98	62.21	1.5230
2013	98.60	4.26	247.97	59.57	1.2420
2014	86.96	3.42	268.11	61.15	1.2194

Note: — indicates the lack of data.

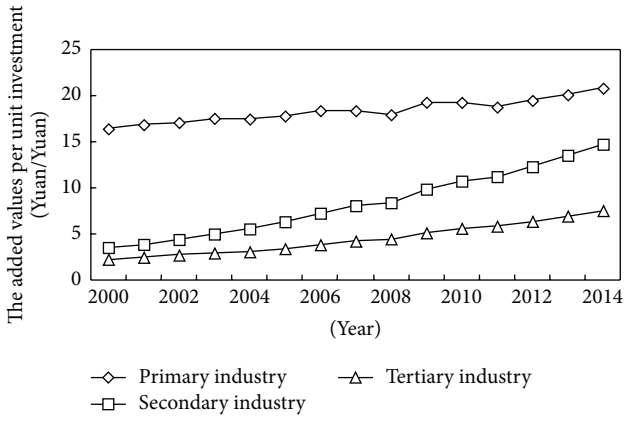

Figure 4: The added values per unit investment of three industries from 2000 to 2014.

show rising trends. By using regression and grey forecast methods, the forecast values in 2015 are shown in Table 3.

The production coefficients of four pollutants and CO_2 emission coefficients from 2000 to 2014 are shown in Table 4. The forecast values of them by different methods in 2015 are shown in Table 5, where, due to the forecast significance, CO_2 emission coefficients are forecasted based on the samples of 2005–2014.

The removal coefficients of COD, ammonia nitrogen, SO_2, and NO_X from 2000 to 2014 are shown in Table 6, and the forecast values of them in 2015 are shown in Table 7.

All the forecast methods are applied according to their premises, so the above results are reasonable theoretically. Due to less effective forecast results, the above indicators can be seen as interval or fuzzy variables. In order to make full use of the forecast results, all the indicators are considered to obey the triangular fuzzy distributions. The triangular fuzzy variable T (u_1, u_2, and u_3) is fully determined by the triplet (u_1, u_2, and u_3) of crisp numbers with $u_1 < u_2 < u_3$, whose membership function is given by

$$\mu(x) = \begin{cases} \dfrac{x - u_1}{u_2 - u_1}, & \text{if } u_1 \le x \le u_2, \\ \dfrac{x - u_3}{u_2 - u_3}, & \text{if } u_2 \le x \le u_3, \\ 0, & \text{otherwise,} \end{cases} \tag{23}$$

Table 5: Forecast results of the production coefficients of four pollutants and CO_2 emissions coefficients in 2015.

Forecast method	The production coefficients of pollutants (t/10^8 Yuan)				CO_2 emissions coefficient (t/t)
	COD	Ammonia nitrogen	SO_2	NO_X	
LR	14.33*	4.24	225.62	45.22	1.1026
GF	74.65	5.32	237.77	53.96	1.1842
ER	80.78	4.51	234.10	50.72	1.1640
PR	114.70	5.84	250.08	56.27	1.3464
QR	127.19	2.91	282.99	70.03	1.0765
CR	57.94	−0.27*	239.55	48.1	0.9863

Note: ∗ indicates that the value does not conform to the reality and should be discarded.

Table 6: The removal coefficients of four pollutants from 2000 to 2014 (unit: t/10^8 Yuan).

Year	The removal coefficients of pollutants			
	COD	Ammonia nitrogen	SO_2	NO_X
2000	22312.87	—	4204.09	—
2001	19102.87	386.51	4054.03	—
2002	11278.36	248.46	2884.60	—
2003	10841.76	247.79	3612.67	—
2004	9002.71	224.17	3286.14	—
2005	7506.24	195.67	3160.82	—
2006	6529.95	449.66	5691.74	13.98
2007	5667.44	204.30	4286.80	11.91
2008	4968.03	206.52	5140.90	18.51
2009	4824.66	272.07	5948.39	50.10
2010	4789.07	363.43	6514.73	27.20
2011	4409.67	195.86	7002.29	29.71
2012	3601.40	145.61	4683.00	60.08
2013	2523.13	103.74	5034.74	77.42
2014	2498.19	92.75	6540.74	84.55

Note: — indicates the lack of data.

Table 7: Forecast results of the removal coefficients of pollutants in 2015 (unit: t/10^8 Yuan).

Forecast method	The removal coefficients of pollutants			
	COD	Ammonia nitrogen	SO_2	NO_X
LR	−1206.00*	135.80	6503.00	86.63
GF	1741.53	×	×	110.45
ER	2085.52	127.80	6655.57	112.52
PR	3099.84	161.19	5659.68	72.30
QR	4924.04	67.34	6539.95	103.59
CR	72.02*	−66.19*	4731.15	113.16

Note: ∗ indicates that the value does not conform to the reality and × indicates the corresponding method does not pass significant test.

where u_1, u_2, and u_3 present the minimum, average, and maximum of all the effective forecast results, respectively. The values of the parameters in triangular fuzzy variables of FCCGP model are shown in Table 8.

4.2. FCCGP Model. According to the 12th five-year plan of Shandong province, the annual average growth rate of GDP is 9%, the industrial structure in 2015 is 7: 48: 45, the annual average growth rate of fixed assets investment is set about 15%, energy consumption intensity and carbon emission intensity should drop by 17% and 18% from 2010, the emissions of COD, ammonia nitrogen, SO_2, and NO_X should drop by 12%, 13.3%, 14.9%, and 16.1%, respectively. GDP, energy consumption intensity, carbon emission intensity, and the emissions of COD, ammonia nitrogen, SO_2, and NO_X in 2010 are 2855.321 billion Yuan, 56.85 tce per million Yuan, 166.62 tons per million Yuan, 295127.6 t, 15441.3 t, 1382874 t, and 1167190 t, respectively, so the targets of above indicators in 2015 are 4393.265 billion Yuan, 46.62 tce per million Yuan, 136.62 tons per million Yuan, 259712.3 t, 13387.6 t, 1176826 t,

Table 8: The values of the parameters in triangular fuzzy variables of FCCGP model.

Variable	u_1	u_2	u_3
I_1	19.74	20.60	21.21
I_2	12.72	15.49	17.31
I_3	6.38	7.78	8.37
P_1	57.94	91.05	127.19
P_2	2.91	4.56	5.84
P_3	225.62	245.02	282.99
P_4	45.22	54.05	70.03
c	0.9863	1.1433	1.3464
E_1	1741.53	2962.73	4924.04
E_2	67.34	123.03	161.19
E_3	4731.15	6017.87	6655.57
E_4	72.30	99.78	113.16

and 979272 t, respectively. Assuming the annual average growth rate of fixed assets investment fluctuates from 12% to 18%, the lower and upper bounds of the fixed assets investment of three industries are 380.13 and 400.49 billion Yuan.

According to the requirements of new normal economy that emphasize structural adjustment, the elimination of energy bottleneck and green low-carbon development, and the effects that Shandong province has achieved at the early time, the GDP proportion of tertiary industry, energy consumption intensity, and CO_2 emission intensity should be paid more attention in 2015. Assuming the predetermined confidence levels of all the targets are $\alpha_1 = 0.9$, $\alpha_2 = 0.9$, $\alpha_3 = 0.95$, $\alpha_4 = 0.9$, $\beta = 0.95$, $\gamma_1 = 0.9$, $\gamma_2 = 0.9$, $\gamma_3 = 0.9$, $\gamma_4 = 0.9$, and $\gamma_5 = 0.95$, the priority orders of three subsystems are economy $\succ$ energy $\succ$ environment, and the weighting factors of deviations corresponding to economy subsystem and environment subsystem are all equal to 1, and a FCCGP model can be constructed as follows:

$$\begin{aligned}
&\min \left\{P_1\left(d_1^+ + d_2^+ + d_3^- + d_4^-\right), P_2 d_5^+,\right.\\
&\quad \left. P_3\left(d_6^+ + d_7^+ + d_8^+ + d_9^+ + d_{10}^+\right)\right\},\\
&G = \sum_{i=1}^{3}\left(I_i \times x_i\right),\\
&\mathrm{Cr}\left\{\frac{I_1 \times x_1}{G} - 0.07 \le d_1^+\right\} \ge \alpha_1,\\
&\mathrm{Cr}\left\{\frac{I_2 \times x_2}{G} - 0.48 \le d_2^+\right\} \ge \alpha_2,\\
&\mathrm{Cr}\left\{0.45 - \frac{I_3 \times x_3}{G} \le d_3^-\right\} \ge \alpha_3,\\
&\mathrm{Cr}\left\{(43932.65 - G) \times 10^{-5} \le d_4^-\right\} \ge \alpha_4,\\
&\mathrm{Cr}\left\{\frac{x_4}{G} - 0.4662 \le d_5^+\right\} \ge \beta,\\
&\mathrm{Cr}\left\{\left(P_1 \times I_2 \times x_2 - E_1 \times x_5 - 295127.6\right) \times 10^{-6}\right.\\
&\quad \left. \le d_6^+\right\} \ge \gamma_1,\\
&\mathrm{Cr}\left\{\left(P_2 \times I_2 \times x_2 - E_2 \times x_5 - 15441.3\right) \times 10^{-5} \le d_7^+\right\}\\
&\quad \ge \gamma_2,\\
&\mathrm{Cr}\left\{\left(P_3 \times I_2 \times x_2 - E_3 \times x_5 - 1382874\right) \times 10^{-7} \le d_8^+\right\}\\
&\quad \ge \gamma_3,\\
&\mathrm{Cr}\left\{\left(P_4 \times I_2 \times x_2 - E_4 \times x_5 - 1167190\right) \times 10^{-7} \le d_9^+\right\}\\
&\quad \ge \gamma_4,\\
&\mathrm{Cr}\left\{\frac{c \times x_4}{G} - 1.3662 \le d_{10}^+\right\} \ge \gamma_5,\\
&\qquad x_i^- \le x_i \le x_i^+,\ i = 1, 2, \ldots, 5,\\
&\qquad 3801.3 \le \sum_{i=1}^{3} x_i \le 4004.9\\
&d_1^+, d_2^+, d_3^-, d_4^-, d_5^+, d_6^+, d_7^+, d_8^+, d_9^+, d_{10}^+ \ge 0,
\end{aligned} \tag{24}$$

where the lower and upper bounds of all the decision variables are shown in Table 2, and the values of triangular distribution parameters of fuzzy variables are shown in Table 8.

4.3. Solution and Discussions. According to the above hybrid intelligent algorithm, the population size $m = 50$, evaluation function parameter $a = 0.05$, crossover probability $p_j = 0.3$, mutation probability $p_b = 0.2$, and generation cycles $T = 3000$. Running the hybrid intelligent algorithm, the optimal solutions of 3Es system optimization model of Shandong province are shown in Table 9. The results of economic priority scenario show that economic subsystem achieves its targets, but energy and environment subsystems do not achieve their targets. The unachieved indicators include the following: the energy consumption intensity is 54.49 tce per million Yuan, the emissions of SO_2 and NO_X are 1566900 t and 979302 t, and CO_2 emission intensity is 139.22 tons per million Yuan.

In economic priority scenario, there are greater differences between the optimized results and the targets in energy and environment subsystems. Considering the importance of environment subsystem for sustainable development, environment priority scenario is defined with the priority orders of three subsystems that are environment $\succ$ economy $\succ$ energy. Running the hybrid intelligent algorithm, the optimal solutions are shown in Table 10. The results show that environment and energy subsystem achieve their targets, but economic subsystem does not achieve its target. The unachieved indicators include the following: the optimized GDP is 4332.194 billion Yuan, and the industrial structure is 8 : 50 : 42.

Table 9: Solution results of FCCGP model of Shandong province in economic priority scenario.

Variable	Solution
x_1^*	130.7
x_2^*	1784.5
x_3^*	2008
x_4^*	37470.8
x_5^*	879.9
d_1^+	0
d_2^+	0
d_3^-	0
d_4^-	0
d_5^+	0.0787
d_6^+	0
d_7^+	0
d_8^+	390074.21
d_9^+	29.57
d_{10}^+	0.0262

Table 10: Solution results of FCCGP model of Shandong province in environment priority scenario.

Variable	Solution
x_1^*	130.7
x_2^*	1716.2
x_3^*	2008
x_4^*	37080.1
x_5^*	1307.6
d_1^+	0.0101
d_2^+	0.0204
d_3^-	0.0103
d_4^-	610.71
d_5^+	0
d_6^+	0
d_7^+	0
d_8^+	0
d_9^+	0
d_{10}^+	0

A scenario endowing the equivalent status for three subsystems is put forward to compare with the first two scenarios. The optimal solutions are shown in Table 11. The results show that all three subsystems do not achieve their targets. The unachieved indicators include the following: the optimized GDP is 4338.292 billion Yuan, the industrial structure is 8 : 50 : 42, the energy consumption intensity is 56.12 tce per million Yuan, and the emissions of SO_2 are 1340146 t.

It can be known from the comparison of three scenarios that the results of the scenario of equivalent status are not improved better than those of environment priority scenario, while environment priority scenario is better than economic priority scenario. Therefore, the optimization results of environment priority scenario can be applied to guide practice

Table 11: Solution results of FCCGP model of Shandong province in the scenario of equivalent status.

Variable	Solution
x_1^*	130.7
x_2^*	1749.6
x_3^*	2008
x_4^*	44278.8
x_5^*	1103.5
d_1^+	0.0007
d_2^+	0.0186
d_3^-	0.0293
d_4^-	549.72
d_5^+	0.0949
d_6^+	0
d_7^+	0
d_8^+	163320
d_9^+	0
d_{10}^+	0

of 3Es system optimization of Shandong province. In 2015, 13.07, 171.62, and 200.8 ten billion Yuan can be invested into the primary, secondary, and tertiary industries, respectively, total energy consumption should be controlled below 370.801 million tce, and 130.76 ten billion Yuan can be invested into environmental pollution control.

The optimization results show that Shandong province should increase the investments in fixed assets of three industries and environmental pollution control in 2015. The investments in fixed assets of the primary, secondary, and tertiary industries in 2015 can be 17%, 4.73%, and 7.59% higher than those in 2014, respectively. The total investments in fixed assets and environmental pollution control in 2015 can be 6.55% and 6.81% higher than those in 2014. Meanwhile, the total energy consumption in 2015 can be merely 2.63% more than that in 2014, which means the growth should be slowed. Practically, Shandong province is undergoing a critical period of structural adjustment at present. The secondary industry consumes considerable amount of energy and causes environmental pollutions and carbon emissions; therefore, it is reasonable to reduce the investment growth of the secondary industry. On the contrary, increasing the investment in the tertiary industry and speeding up its development can reduce energy consumption and environmental pollutions. In addition, the carrying capacity of energy resources in Shandong province has been continuously improving, so it is necessary to reduce the growth of energy consumption while ensuring economic development, which means that Shandong province should strengthen energy conservation, improve energy efficiency, and develop alternative energy sources.

5. Conclusions

In this study, we have analyzed the structure of 3Es system and selected the typical indicators to demonstrate the main causal relationships. The target parameters and decision variables

are set and a FCCGP model is put forward for 3Es system optimization. In the FCCGP model, uncertain parameters are fuzzy variables, and fuzzy chance constraints are satisfied with certain confidence levels. The proposed model is essentially flexible, and any number and form of fuzzy goals and constraints can be contained into it. A hybrid intelligent algorithm including fuzzy simulation and genetic algorithm is put forward for solving the uncertain model. Depending upon the nature of the study region, the user can modify the model and algorithm inputs to get desired outputs. After the empirical analysis on Shandong province, we can conclude that the parameters of 3Es system optimization can be regarded as triangular fuzzy numbers, and FCCGP models with fuzzy variables can demonstrate the relations of interaction among three subsystems. The results of 3Es system optimization of Shandong province testify the feasibility of FCCGP models, which can be applied to guide the practice of 3Es system optimization so as to realize their harmonious development. According to the optimization results, Shandong province should obey the rule of environment priority. In this scenario, 3Es system can realize relatively more scientific development, although it may lower the economic development to a certain extent.

Limited by the definition of research object and availability of data, in this paper, we neither include imports and exports, household consumption and other contents into economic subsystem, nor take into consideration land, forest, mineral, water resources, population, science and technology, and other subsystems. This weakened the complex relationship between each subsystem in some certain extent and might affect the objectivity of the programming results, which should be improved in the future studies.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Uncertain Risk Assessment of Knowledge Management: Based on Set Pair Analysis

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Since the knowledge resource becomes an important part of enterprise resources, the knowledge management risks could significantly affect the enterprise operation efficiency. Controlling knowledge management risks is one of the enterprise management tasks; the managers and researchers focus on how to effectively evaluate the risks. This paper aims to solve this problem and puts forward an evaluation model of the uncertain risks of knowledge management. Based on set pair theory, a model is established to identify the knowledge management risk. Through the concept of connection number, knowledge management risk is divided into five levels. Meanwhile, the development trend of knowledge management risk is classified into same tendency, equal tendency, and contrary tendency by the concept of set pair theory. The application of this model is empirically verified with Chinese enterprises. Through both static and dynamic evaluations of the knowledge management risk, this paper can effectively analyze risk development trend and provide decision support for the enterprise manager about the uncertain risks of knowledge management.

1. Introduction

Knowledge is one of the most important resources of an enterprise. Skillful knowledge management can bring significant benefits including labor productivity growth, an increase in quality of provided services, and also a strengthening of the competitive position of an enterprise [1]. Compared to other kinds of assets, knowledge has a unique nature in which the more it is used the more its value increases [2]. While benefiting from knowledge management, enterprises also face the uncertain risks from it. Knowledge management risk exists in the process of acquiring, integrating, and sharing knowledge, as well as in innovation and knowledge application, and it can bring loss to enterprise for some reasons. Some experts say that the failure ratio of knowledge management programs is between 50% and 70%, which makes the evaluation and prevention of knowledge management risks especially important.

The research on risk management in academic world exists early, while the research on knowledge management risk appears later. Recently, the study on knowledge management risk has spread out. Ruggles in the research of factors influencing knowledge management application showed that uncoordinated organization culture is the biggest hindrance of knowledge management [3]. McBriara et al. studied the influence of knowledge management risk on knowledge management planning [4]. Elias and Wright pointed out that reasons behind knowledge management risks can be improper information policy, employee loss, and poor information transferability [5]. Perrott after combining the actual company situation proposed the top-down knowledge management system by establishing risk management committee including CEO, CFO, and risk management staff to monitor knowledge management risk [6]. Now, there are also lots of studies on knowledge management risk evaluation. Huang stated the contents of knowledge management risks and methods of how to identify and evaluate enterprise knowledge management risk from risk factors analysis, risk frequency, scope, gains, and losses estimation [7]. Zhang et al. put forward a multi-index complex evaluation method based on language evaluation for enterprise knowledge management risk [8]. Massingham has researched the cognitive constraints in knowledge risk management by using case study method [9]. Li and Zhang used extension method to evaluate

enterprise information management risk [10]. Bamakan and Dehghanimohammadabadi propose a new quantitative risk analysis and assessment methodology, which is based on AHP and Monte Carlo simulation [11].

In general, knowledge management risk evaluation methods can be classified into qualitative method, quantitative method, and qualitative combining quantitative method, such as analytic hierarchy process, grey correlation method, and genetic algorithm. However, each method has certain limitations [12]. Qualitative method is fairly subjective and can be greatly affected by the evaluator; quantitative method describing the evaluation results through the objective data could make the result look too simple and cover up the role of other factors. The combination of qualitative and quantitative methods is the mainstream at this stage, which mainly includes the fuzzy comprehensive evaluation method and expert scoring method. These methods can evaluate the risk level of knowledge management; however, they cannot predict the risk development trend, which is exactly crucial information for enterprise managers. Since knowledge management risk refers to the uncertainties caused by variable factors during managing process and set pair theory is the mathematical method for uncertain issues with its core to describe uncertain issue by same-indefinite-contrary connection number and to predict system development trend [13], this paper introduced set pair analysis to evaluate knowledge management risk.

2. Models and Methods

2.1. Fundamentals of Set Pair Theory. Set pair analysis was first proposed by Chinese scholar Zhao in 1989 and it is a method to deal with fuzzy and uncertain problems [14]. Set pair is formed by two related sets, such as system and engineering, information and control, and production and sales. The basic idea is to do the same, indefinite, and the contrary analysis and quantitative description in the specific problem situation and then to get the connection degree expression based upon which one can study related issues of the system [15].

In set pair analysis, connection number [16] is an important concept and its general expression is

$$\mu = \frac{S}{N} + \frac{F}{N}m + \frac{P}{N}n. \tag{1}$$

In this expression, N stands for all features of the set pair, S stands for the same features, F stands for the indefinite features, and P stands for the contrary features. The connection among them is $N = S + P + F$. If we consider $a = S/N$, $b = F/N$, and $c = P/N$, then we can easily get this:

$$\mu = a + bm + cn. \tag{2}$$

According to expression (1), we know the relationship of a, b, and c is $a + b + c = 1$, with a, b, and c belonging to $[0, 1]$, $m \in [-1, 1]$, and $n = -1$, a being the same degree, b the indefinite degree, and c the contrary degree. The coefficient of "a" is 1, completely in the positive level. The coefficient of "b" is $[-1, 1]$, some in the positive level and some in the negative level. The coefficient of "c" is -1, completely in the negative level. If we use "$\succ$" to express the location of a, b, and c, then we get $a \succ b \succ c$, with "$\succ$" meaning "positive" [17].

2.2. Five-Element Connection Number. By the set pair analysis, we know connection number $\mu = a+bm+cn$ is a system in which a, b, c, and j reflect the macro level, i reflects the micro level, and bi reflects both. So we can unfold it to express the hierarchy of the system, which is $\forall a, b, c \in [0, 1]$, $m \in [-1, 1]$, and $n = -1$ and its general expression is

$$\mu = a + b_1m_1 + b_2m_2 + \cdots + b_nm_n + cn. \tag{3}$$

When $n = 3$, we can get

$$\mu = a + b_1m_1 + b_2m_2 + b_3m_3 + cn, \tag{4}$$

$$\text{Or } \mu = a + bi + cj + dk + el. \tag{5}$$

This expression is the so called five-element connection number, with a being the same degree, b being the indefinite same degree, c being the indefinite center degree, d being the indefinite contrary degree, and e being the contrary degree. All of them are called connection degree, with $a, b, c, d, e \in [0, 1]$, $a + b + c + d + e = 1$, $i \in [0, 1]$, $j \in [0, 0]$, $k \in [-1, 0]$, and $l = -1$. The relationship between a, b, c, d, and e is $a \succ b \succ c \succ d \succ e$. In the information risk assessment, we can combine risk grade with the five-element connection number to further define the risk degree by using a for "lowest risk," b for "lower risk," c for "medium risk," d for "higher risk," and e for "highest risk."

2.3. Evaluation Model for Risk Uncertainties. According to the fundamentals of set pair and five-element connection number, the influence factor of knowledge management risk sets is $U = (\mu_1, \mu_2, \ldots, \mu_n)$ and the weight matrix of influence factors is $W = (\omega_1, \omega_2, \ldots, \omega_n)$. Knowledge management risk evaluation of the people under survey for the influence factors can be divided into five classes, "lowest risk," "lower risk," "medium risk," "higher risk," and "highest risk." Combining the weights of affecting factors, we can get the following evaluation model [18]:

$$\begin{aligned} V = {} & (\omega_1, \omega_2, \ldots, \omega_n) \\ & \cdot \begin{Bmatrix} \mu_{11} & \mu_{12} & \mu_{13} & \mu_{14} & \mu_{15} \\ \mu_{21} & \mu_{22} & \mu_{23} & \mu_{24} & \mu_{25} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \mu_{n1} & \mu_{n2} & \mu_{n3} & \mu_{n4} & \mu_{n5} \end{Bmatrix} \begin{pmatrix} 1 \\ i \\ j \\ k \\ l \end{pmatrix} = \sum_{t=1}^{n} \omega_t \mu_{t1} \\ & + \sum_{t=1}^{n} \omega_t \mu_{t2} i + \sum_{t=1}^{n} \omega_t \mu_{t3} j + \sum_{t=1}^{n} \omega_t \mu_{t4} k + \sum_{t=1}^{n} \omega_t \mu_{t5} l. \end{aligned} \tag{6}$$

In this model, $E = \begin{pmatrix} 1 & i & j & k & l \end{pmatrix}^T$ is the coefficient matrix. According to set pair theory,

$a = \sum_{t=1}^{n} \omega_t a_{t1}$ reflects the "lowest risk,"
$b = \sum_{t=1}^{n} \omega_t u_{t2} i$ reflects the "lower risk,"
$c = \sum_{t=1}^{n} \omega_t u_{t3} j$ reflects the "medium risk,"
$d = \sum_{t=1}^{n} \omega_t u_{t4} k$ reflects the "higher risk,"
$e = \sum_{t=1}^{n} \omega_t u_{t5} l$ reflects the "highest risk."

2.4. Risk Trend Analysis Method

2.4.1. Partial Connection Number. Connection number can reflect the structure function of the system and the priorities of system levels. Partial connection number is the associate function of connection function [19] which can reflect the development trend of the system.

Let us define each partial connection number of five-element connection number [20].

First partial connection number is

$$\partial\mu = \partial a + i\partial b + j\partial c + k\partial d, \tag{7}$$

with $\partial a = a/(a+b)$, $\partial b = b/(b+c)$, $\partial c = c/(c+d)$, and $\partial d = d/(d+e)$.

Second partial connection number is

$$\partial^2\mu = \partial\left(\partial\mu\right) = \partial^2 a + i\partial^2 b + j\partial^2 c, \tag{8}$$

with $\partial^2 a = \partial a/(\partial a + \partial b)$, $\partial^2 b = \partial b/(\partial b + \partial c)$, $\partial^2 c = \partial c/(\partial c + \partial d)$.

Third partial connection number is

$$\partial^3\mu = \partial\left(\partial^2\mu\right) = \partial^3 a + i\partial^3 b, \tag{9}$$

with $\partial^3 a = \partial^2 a/(\partial^2 a + \partial^2 b)$. $\partial^3 b = \partial^2 b/(\partial^2 b + \partial^2 c)$.

Fourth partial connection number is

$$\partial^4\mu = \partial\left(\partial^3\mu\right) = \partial^4 a, \tag{10}$$

with $\partial^4 a = \partial^3 a/(\partial^3 a + \partial^3 b)$.

From expression (7), we can tell a in μ originates from b, and $\partial a = a/(a+b)$ reflects the development level in quantity; b originates from c, and $\partial b = b/(b+c)$ reflects the development level in quantity; c originates from d, and $\partial c = c/(c+d)$ reflects the development level in quantity; d originates from e, and $\partial d = d/(d+e)$ reflects the development level in quantity. By the same token, we can get the meaning of other partial connection numbers.

2.4.2. Set Pair Tendency. Set pair tendency can reflect the same-indefinite-contrary degree of two sets [21]. In the five-element connection $\mu = a + bi + cj + dk + el$, when $e \neq 0$, we call a/e set pair tendency, or shi$(H) = a/e$. Its specific meaning is as follows. When $a > e$, $a/e > 1$, the two sets are in the same tendency. When $a < e$, $a/e < 1$, the two sets are in the contrary tendency. When $a = e$, $a/e = 1$, the two sets are in the equal tendency [22]. In the assessment of knowledge management risk, we can recognize "low risk" as the ideal reference set and get shi(risk) $= a/e$. Similarly, we can classify the knowledge management risk into three types: same tendency, contrary tendency, and equal tendency.

When the knowledge management risk is in the same tendency, it means that actual and ideal risk has the same trend and the actual risk is low. At this point, the managers should pay attention to the first partial connection number of each influence factor and invest more into influence factors in the contrary tendency to make it change to same tendency.

When the knowledge management risk is in the equal tendency, it means the actual risk is in the middle and the system risk is medium. At this point, managers should focus on the first partial connection number and prevent the risk from turning into contrary tendency.

When the information risk is in the contrary tendency, it means the actual risk is higher and the system risk is higher. At this point, managers should concentrate on every factor which is in contrary tendency and push them to change to equal tendency and then to same tendency.

3. Empirical Analysis

Due to the human uncertainties, knowledge itself and knowledge management environment, there are unavoidable risks in the process of using knowledge management methods to solve problems or in conducting knowledge management programs. Risks come along with profits, so it is of great importance to identify, evaluate, and manage risks for the enterprise when applying knowledge management. So far, there are lots of researches on the composition of knowledge management risk. Elias and Wright pointed out that reasons behind knowledge management risks can be improper information policy, employee loss, and poor information transferability [5]. Li and Zhang thought there are human resources risk, information risk, organization risk, technology risk, information process risk, and capital risk in knowledge management risk that enterprises face [10].

After combining the research results of scholars and the authors' investigation of manufacturing enterprises, this paper suggests five risks of knowledge management: human factor risk, information risk, organization risk, technology risk, and market risk. Meanwhile, the five risks can be measured by subordinate influencing factors. All these are shown as in Table 1. Here we will explain the subordinate influencing factors. Employee loss means the probability that employees may leave the enterprise. Secret leakage is a risk that anyone in the enterprise may divulge a secret to the competitors, especially the intellectual property. Professional skill means the personal qualities and abilities of the employees. Information transform is the deviation between the explicit and tacit knowledge conversion. Information spill means there is a certain risk that, during the storage of knowledge, it may be stolen by hacker or spilled by internal staffs. Information transfer represents the risk during the process of transfer. Information property stands for the knowledge itself, which means the forms of knowledge. Strategy positioning is the positioning which the company sets for itself. Enterprise policy and enterprise capital stand

Table 1: Five-element connection number table for influencing factors of evaluating knowledge management.

Risks	Risk factors	Weight	Five-element connection number	
			Lowest, lower, medium, higher, highest	Tendency
Human factor risk (0.18)	Employee loss	0.18	$0.01 + 0.15i + 0.30j + 0.30k + 0.24l$	Contrary tendency
	Secret leakage	0.28	$0.22 + 0.21i + 0.30j + 0.15k + 0.12l$	Same tendency
	Professional skills	0.54	$0.15 + 0.19i + 0.20j + 0.21k + 0.25l$	Contrary tendency
	Subtotal	1.00	$0.14 + 0.19i + 0.25j + 0.21k + 0.21l$	Contrary tendency
Information risk (0.17)	Information transform	0.12	$0.12 + 0.13i + 0.10j + 0.27k + 0.38l$	Contrary tendency
	Information spill	0.36	$0.14 + 0.10i + 0.28j + 0.22k + 0.26l$	Contrary tendency
	Information transfer	0.34	$0.27 + 0.30i + 0.20j + 0.13k + 0.10l$	Same tendency
	Information property	0.18	$0.11 + 0.28i + 0.32j + 0.19k + 0.10l$	Same tendency
	Subtotal	1.00	$0.18 + 0.20i + 0.24j + 0.19k + 0.19l$	Contrary tendency
Organization risk (0.20)	Strategy positioning	0.44	$0.12 + 0.19i + 0.48j + 0.11k + 0.10l$	Same tendency
	Enterprise policy	0.30	$0.19 + 0.11i + 0.31j + 0.20k + 0.19l$	Equal tendency
	Enterprise capital	0.26	$0.02 + 0.10i + 0.28j + 0.37k + 0.23l$	Contrary tendency
	Subtotal	1.00	$0.12 + 0.14i + 0.38j + 0.20k + 0.16l$	Contrary tendency
Technology risk (0.13)	Management technique	0.46	$0.12 + 0.28i + 0.38j + 0.11k + 0.11l$	Same tendency
	System usage	0.54	$0.42 + 0.25i + 0.21j + 0.08k + 0.04l$	Same tendency
	Subtotal	1.00	$0.28 + 0.26i + 0.29j + 0.09k + 0.07l$	Same tendency
Market risk (0.32)	Customer satisfaction	0.21	$0.05 + 0.11i + 0.28j + 0.31k + 0.25l$	Contrary tendency
	Time delay	0.63	$0.11 + 0.19i + 0.20j + 0.29k + 0.21l$	Contrary tendency
	Outside change	0.16	$0.02 + 0.07i + 0.20j + 0.23k + 0.48l$	Contrary tendency
	Subtotal	1.00	$0.08 + 0.15i + 0.22j + 0.28k + 0.26l$	Contrary tendency
Total		1.00	$0.14 + 0.18i + 0.27j + 0.21k + 0.20l$	Contrary tendency

The meaning of some risk factors:
Professional skills: the ability of staff is not enough to do the work.
Information transform: the deviation between the explicit and tacit knowledge conversion.
System usage: the employees reject the system or use it incorrectly.
Time delay: the speed of latest knowledge absorption is slow.

for the emphasis on knowledge management. Management technique is the method that managers take to control the risks. System usage means the employees reject the system or use it incorrectly. Time delay is the speed of latest knowledge absorption being slow, which could increase the risk of knowledge management. Outside change means the markets environments changes which could bring risks to the knowledge management.

When we compare all the risk factors to the relative standard, we can classify the risk into lowest risk, lower risk, medium risk, higher risk, and highest risk. In this way, we can build an evaluation model of knowledge management risk to analyze the influencing factors.

Weight of the influencing factors will be decided by integrative assigning method. The subjective assigning method by analytic hierarchy process (AHP) is suitable for subjects affected by many factors that are clearly distinctive, and the objective assigning method by entropy is to decide weight by decision matrix. After going through the subjective and objective assigning methods, the multiplicative method of integrative assigning is used to treat the two results and get the final reasonable weight for the risk evaluation factors. The detailed weight is shown in Table 1. This survey takes manufacturing enterprise as the investigation subject and questionnaires are designed according to maximum difference. We did the survey by interviewing the MBA students who worked as managers in the manufacturing enterprises and let them fill in the questionnaire we designed. Among the 300 copies sent out to the managers in the manufacturing enterprises, 247 are back and 208 are valid. The empirical research includes 300 managers in 20 manufacturing enterprises. We have surveyed 8 automobile manufacturing enterprises and 6 electronic products manufacturing enterprises and we have handed out 120 questionnaires to the automobile manufacturing enterprises managers and 90 questionnaires to the electronic products manufacturing enterprises managers. On the other hand, we also have investigated 6 equipment manufacturing enterprises through the network and surveyed 90 managers of the enterprises via e-mail and 75 was the value which had been returned. The data and calculation results are shown in Tables 1, 2, and 3.

After analyzing the five-element connection number based on set pair theory, we can get below results for Table 1 data.

The five-element connection number for manufacturing enterprise is $0.14 + 0.18i + 0.27j + 0.21k + 0.20l$, with set pair $\text{shi}(H) = a/e = 0.7$ in the contrary tendency, which means Chinese manufacturing managers today have high risk expectation on knowledge management process. Within it, human factor risk, information risk, organization risk,

Table 2: Partial connection number table for knowledge management evaluation.

Risks	Risk factors	Partial connection number							
		First	Tendency	Second	Tendency	Third	Tendency	Fourth	Tendency
Human factor risk (0.18)	Employee loss	$0.06 + 0.33i + 0.50j + 0.56k$	Contrary	$0.16 + 0.40i + 0.47j$	Contrary	$0.28 + 0.46i$	Contrary	0.38	Contrary
	Secret leakage	$0.51 + 0.41i + 0.67j + 0.56k$	Contrary	$0.55 + 0.38i + 0.55j$	Equal	$0.59 + 0.41i$	Same	0.59	Same
	Professional skills	$0.44 + 0.49i + 0.49j + 0.46k$	Contrary	$0.48 + 0.50i + 0.52j$	Same	$0.49 + 0.49i$	Equal	0.50	Same
	Subtotal	$0.43 + 0.43i + 0.54j + 0.50k$	Contrary	$0.50 + 0.45i + 0.52j$	Contrary	$0.53 + 0.46i$	Same	0.53	Same
Information risk (0.17)	Information transform	$0.48 + 0.57i + 0.27j + 0.42k$	Same	$0.46 + 0.68i + 0.39j$	Same	$0.40 + 0.63i$	Contrary	0.39	Contrary
	Information spill	$0.58 + 0.26i + 0.56j + 0.46k$	Same	$0.69 + 0.32i + 0.55j$	Same	$0.68 + 0.37i$	Same	0.65	Same
	Information transfer	$0.47 + 0.60i + 0.61j + 0.57k$	Contrary	$0.44 + 0.50i + 0.52j$	Contrary	$0.47 + 0.49i$	Contrary	0.49	Contrary
	Information property	$0.28 + 0.47i + 0.63j + 0.66k$	Contrary	$0.38 + 0.43i + 0.49j$	Contrary	$0.47 + 0.47i$	Equal	0.50	Equal
	Subtotal	$0.46 + 0.46i + 0.56j + 0.50k$	Contrary	$0.50 + 0.45i + 0.53j$	Contrary	$0.53 + 0.46i$	Same	0.53	Same
Organization risk (0.20)	Strategy positioning	$0.39 + 0.28i + 0.81j + 0.52k$	Contrary	$0.58 + 0.26i + 0.61j$	Contrary	$0.69 + 0.30i$	Same	0.70	Same
	Enterprise policy	$0.63 + 0.26i + 0.61j + 0.51k$	Same	$0.71 + 0.30i + 0.54j$	Same	$0.70 + 0.36i$	Same	0.66	Same
	Enterprise capital	$0.17 + 0.26i + 0.43j + 0.62k$	Contrary	$0.39 + 0.38i + 0.41j$	Contrary	$0.51 + 0.48i$	Same	0.51	Same
	Subtotal	$0.45 + 0.27i + 0.65j + 0.56k$	Contrary	$0.62 + 0.30i + 0.54j$	Same	$0.68 + 0.36i$	Same	0.65	Same
Technology risk (0.13)	Management technique	$0.30 + 0.42i + 0.78j + 0.50k$	Contrary	$0.41 + 0.35i + 0.61j$	Contrary	$0.54 + 0.37i$	Same	0.59	Same
	System usage	$0.63 + 0.54i + 0.72j + 0.67k$	Contrary	$0.54 + 0.43i + 0.52j$	Same	$0.56 + 0.45i$	Same	0.55	Same
	Subtotal	$0.52 + 0.48i + 0.75j + 0.57k$	Contrary	$0.52 + 0.39i + 0.57j$	Contrary	$0.57 + 0.40i$	Same	0.59	Same
Market risk (0.32)	Customer satisfaction	$0.31 + 0.28i + 0.47j + 0.55k$	Contrary	$0.53 + 0.37i + 0.46j$	Same	$0.59 + 0.45i$	Same	0.57	Same
	Time delay	$0.37 + 0.49i + 0.41j + 0.58k$	Contrary	$0.43 + 0.54i + 0.41j$	Same	$0.44 + 0.57i$	Contrary	0.44	Contrary
	Outside change	$0.22 + 0.26i + 0.47j + 0.32k$	Contrary	$0.46 + 0.36i + 0.59j$	Contrary	$0.56 + 0.38i$	Same	0.60	Same
	Subtotal	$0.35 + 0.42i + 0.43j + 0.52k$	Contrary	$0.46 + 0.49i + 0.45j$	Same	$0.48 + 0.52i$	Contrary	0.48	Contrary
Total		$0.44 + 0.40i + 0.55j + 0.52k$	Contrary	$0.52 + 0.42i + 0.52j$	Equal	$0.55 + 0.45i$	Same	0.55	Same

Table 3: Set pair variation table for knowledge management evaluation.

Risks	Risk factors	Five-element connection number set pair tendency	First set pair tendency	Second set pair tendency	Third set pair tendency	Fourth set pair tendency
Human factor risk	Employee loss	0.04	0.11	0.33	0.62	0.38
	Secret leakage	1.83	0.92	1.02	1.44	0.59
	Professional skills	0.60	0.97	0.92	0.99	0.50
	Subtotal	0.67	0.87	0.96	1.15	0.53
Information risk	Information transform	0.32	1.16	1.17	0.64	0.39
	Information spill	0.54	1.27	1.25	1.86	0.65
	Information transfer	2.70	0.84	0.85	0.96	0.49
	Information property	1.10	0.43	0.77	1.01	0.50
	Subtotal	0.94	0.93	0.95	1.13	0.53
Organization risk	Strategy positioning	1.20	0.74	0.95	2.32	0.70
	Enterprise policy	1.00	1.24	1.30	1.96	0.66
	Enterprise capital	0.09	0.27	0.94	1.05	0.51
	Subtotal	0.75	0.78	1.15	1.89	0.65
Technology risk	Management technique	1.09	0.60	0.68	1.47	0.59
	System usage	10.5	0.94	1.02	1.23	0.55
	Subtotal	4.00	0.91	0.91	1.42	0.59
Market risk	Customer satisfaction	0.20	0.56	1.14	1.31	0.57
	Time delay	0.52	0.63	1.04	0.77	0.44
	Outside change	0.04	0.69	0.78	1.49	0.60
	Subtotal	0.31	0.67	1.01	0.93	0.48
Total		0.70	0.84	1.01	1.23	0.55

and market risk are in the contrary tendency, and only the technology tendency is in same tendency.

The five-element connection number for human factor risk is $0.14 + 0.19i + 0.25j + 0.21k + 0.21l$ and, in the contrary tendency, indicates that human factor risk is high. In this type of risk, employee loss and professional skills are in the contrary tendency and secret leakage is in same tendency, suggesting that employee loss is serious and professional skills need further improvement, while secret leakage risk is low.

The five-element connection number for information risk is $0.18 + 0.20i + 0.24j + 0.19k + 0.19l$ and is in the contrary tendency. The information transform and information spill are in the contrary tendency and the other two are in same tendency, which means that, in manufacturing enterprise, explicit information and implicit information transform can have deviation easily and information is easy to be imitated or gained by competitors.

The five-element connection number for organization risk is $0.12 + 0.14i + 0.38j + 0.20k + 0.16l$ and is in the contrary tendency, with strategy positioning and enterprise policy in same tendency and equal tendency, respectively, and enterprise capital in contrary tendency, indicating that, in manufacturing enterprise capital, usage efficiency is not high and input and output measurements are not correct.

The five-element connection number for technology risk is $0.28 + 0.26i + 0.29j + 0.09k + 0.07l$ and is in same tendency, with knowledge management technology and system usage in same tendency, suggesting small risk.

The five-element connection number for market risk is $0.08 + 0.15i + 0.22j + 0.28k + 0.26l$ and is in contrary risk, with customer satisfaction, time delay, and outer environment all in contrary tendency, which means that market changes fast and customers have higher product requirement; however, the product design and production of today's manufacturing enterprise can hardly follow the consumer's taste change.

According to set pair theory, data in Table 2 can be analyzed as shown below.

The first partial connection number for knowledge management of manufacturing enterprise is $0.44 + 0.40i + 0.55j + 0.52k$ and is in contrary tendency, showing rising risk in knowledge management of today's redt, the first partial connection number of human factor, information, organization, technology, and market are all in the contrary tendency, suggesting all the risks are increasing. Among the 15 risk factors, only information transform, information spill, and enterprise policy are in the same tendency, and the other 12 factors are in the contrary tendency. Managers should pay attention to all the risk factors of the partial connection number that are in contrary tendency and take actions to prevent further increasing of the risks.

The second partial connection number for knowledge management of manufacturing enterprise is $0.52 + 0.42i + 0.52j$ and is in equal tendency, while the third partial connection number is $0.55 + 0.45i$, in equal tendency, and the fourth is 0.55, bigger than 0.5, and is in equal tendency.

Based on set pair theory, we can draw the following conclusions for data in Table 3.

The set pair tendency of the whole five-element connection number is 0.70, less than 1, and is in the contrary tendency. The set pair tendencies of the five risks are 0.67, 0.94, 0.75, 4.00, and 0.31, respectively, with four in contrary tendency, accounting for 80%. Only technology risk is in same tendency, which means the technology risk is the lowest in the five factors, because in the survey, the managers all think the system usage is the progress which could be controlled easily and the system usually should be trusted. Market risk set pair tendency is the smallest, meaning market risk is the highest. In human factor risk, employee loss is the highest risk, while in information risk, information transform is the highest risk, and in organization risk, enterprise capital is the highest risk, and in market risk, outside environment change is the highest risk. Enterprise managers should pay great attention to the four risk factors and take measures for prevention. From the set pair tendency of the first partial connection number, information transform, information spill, and enterprise policy among the 15 risk factors are bigger than 1 for set pair tendency and are in the same tendency with others in contrary tendency. This means today's manufacturing enterprise faces increasing knowledge management risk.

The set pair tendency of all the manufacturing enterprise is 0.7, 0.84, 1.01, 1.23, and 0.55, respectively, indicating that the risks are moving towards same tendency with big step, which requires the managers to take actions to facilitate the change in order to reduce risk.

4. Conclusions

Chinese manufacturing enterprise now faces great and rising risk in knowledge management, which pushes managers to take measures to reduce the risk factors in contrary tendency. For instance, in human factor risk, employee welfare should be increased to lower the employee loss rate, and employee training or hiring employees with better professional skills is needed to improve the overall employee professional skill; leaders should communicate with employees to find out the employees' needs, enhance organizational cohesion, and avoid the employees' departure due to dissatisfaction with the enterprise. In organization risk, the managers should build a positive and open enterprise culture to promote employees and enterprises set up the shared values and vision. In addition, open enterprise interior environment atmosphere can not only make employees more likely to accept new things and effectively avoid repellency of knowledge management system, but also accelerate the speed of knowledge innovation. In technology risk, enterprises should strengthen staff training and enhance the staff's comprehensive quality and professional skills. In market risk, the managers should pay attention to the competitors. It can help enterprise understand the market changes; we can get some knowledge of the competitors when they collect the market information.

Set pair analysis is a mathematical tool to study uncertain system. Using the connection number concept of set pair theory to evaluate knowledge management risk can get the static tendency of the risks, as well as the prediction of their development trend, realizing the way of combining static and dynamic and quality and quantity for the evaluation. From the above analysis, we can see that the connection number of the risks can be in same, equal, and contrary tendency, moving forward in waving momentum. This requires the manager to make preparations to identify the risk development tendency and take measurements in human, capital, and other aspects to lower risks. Set pair analysis can also be supplied to research information risk evaluation, such as the information diffusion system. At the same time, it can be used to evaluate the construction program risk, such as the natural gas pipeline construction.

When analyzing the set pair tendency, this paper did not differentiate the weakness and strength of each tendency, which needs further discussion in future research.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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