Research Article

Supply Interruption Supply Chain Network Model with Uncertain Demand: An Application of Chance-Constrained Programming with Fuzzy Parameters

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The downstream supply interruption of manufacturers is a disaster for the company when the demand is uncertain in the market; a fuzzy programming with fuzzy parameters model of supply interruption supply chain network is established by simulating market operation rules. The aim of the current study is to build a fuzzy chance-constrained programming method which is developed for supporting the uncertainty of demand. This method ensured that the fuzzy constraints can be satisfied at specified confidence levels, leading to cost-effective solutions under acceptable risk magnitudes. Finally, through the case of the electronic product manufacturing enterprise, the feasibility and effectiveness of the proposed model are verified by adopting a sensitivity analysis of capacity loss level and minimizing objective function. Numerical simulation shows that selecting two manufacturing centers can effectively reduce the supply chain cost and maintain business continuity.

1. Introduction

In the actual production process, the uncertainty of demand caused by the individualization and diversity requirements of consumers often impacts the productivity of manufacturers [1–3]. According to the Japan Economic Daily, Foxconn's original 60 iPhone XR production lines, in November 2018, due to insights into changes in product demand in the market, 45 production lines were decided to start and the remaining 15 production lines were suspended indefinitely because the manufacturer's production line usually changed according to user demand. This crisis is manifested in the risk of disruption to the supply capacity of the end customer. For example, in 2019, Xiao Mi's new mobile phone Xiaomi 9 was sold out in a minute after the release of Jing Dong due to insufficient stocking, which seriously affected the profit of Xiaomi enterprises. The Vivo IQOO mobile phone is also popular, but the supply is sufficient, effectively avoiding the risk of supply interruption. Analysis of the underlying causes shows that the reliability of the manufacturing centers of the two companies is the main source of the supply disruption crisis. Among them, Xiaomi Company is organized by Foxconn and Inventec Appliances Corp. Foundry companies have their own interests, usually not only for Xiaomi's enterprises, but also preferentially produce orders with large profits, so there will be a risk of disruption of Xiaomi's mobile phone supply. The Vivo Company has four production bases in Dongguan, Chongqing, New Delhi, India, and Jakarta, Indonesia. 122 modern production lines can produce 10 million mobile phones per month, and the manufacturing center of Vivo is dedicated to the production of Vivo mobile phones and service, thus providing a stable source of supply for mobile phone sales.

The solution to supply disruption is usually to form different supply chain risk management models based on the

analysis of the company's competitive strategy [4–6]. Because the supply chain flexible design can effectively solve the integration of market and enterprise, it is of great significance to deal with potential supply chain risks [7]. Often, the company's flexible design of the supply chain after determining its strategic target market requires attention to two main characteristics: supply chain scope (local or global) and competitive priority (responsiveness or cost reduction) [8–10]. At this stage, it is important to understand the supply chain vulnerability caused by supply disruptions, which will help to achieve a dynamic adaptive elastic supply chain. Figure 1 illustrates the dynamic process of supply chain resiliency design in this paper and demonstrates the optimization process of supply chain risk management to alleviate supply chain risk. This process is mainly achieved through supply chain resiliency design [11–14].

At present, the research on the risk of supply interruption is rich, mainly including multisupplier strategy research [15–17]; the establishment of emergency inventory [18, 19]; alternative suppliers [20, 21]; contract theory to reduce futures commodity risks [22]; [23–25]. Facility safety is improved to cope with the supply disruption crisis caused by natural risks [26, 27], but the above research usually lacks a flexible mechanism and cannot respond to supply disruption crisis according to supply chain structure adjustment and different situational flexibility change strategies [28–31]. However, research methods for uncertainty requirements include the use of fuzzy programming or robust optimization to deal with uncertainty, but these methods usually require a large number of samples, but in fact, the number of samples is limited and only can get the range of sample values rather than the exact value [8, 32, 33].

Therefore, this paper constructs a three-tier supply chain network model, consisting of one supplier, multiple manufacturers, multiple customers, and a manufacturing company and studies the risk of supply disruption when demand is uncertain [34–40]. The fuzzy number of uncertain demand is converted into the determined risk of supply interruption risk, and the logistics supply is used to coordinate the supply capacity of reliable and unreliable manufacturing centers for supply chain flexibility design, to meet the needs of users while maintaining the stability of the supply chain and reducing the risk of supply [41–45].

2. Model Assumptions and Construction

2.1. Description of the Problem. A three-tier supply chain network of suppliers, multiple manufacturers, and multiple-end customers, is built as the demand is uncertain, as shown in Figure 2. Assume that the parts in the market are supplied by one supplier, and the manufacturing center organizes the production according to the customer's needs. The reliable manufacturing center produces according to its production capacity to meet the needs of customers. The unreliable manufacturer can adjust the production plan according to its interests and may not meet the needs of the customer. This means that the quantity of products provided by reliable manufacturing centers is stable, while the quantity of products provided by unreliable manufacturers is unstable.

The quantity of products required, and the shortage can be met by the reliable manufacturing center through the coordination of logistics functions from the reliable manufacturing center.

Figure 2 shows two manufacturing centers, which are two types of manufacturing centers. In a supply chain, each type can have multiple manufacturing centers. Among them, the manufacturing center cannot exceed the maximum production capacity of the customer, and the supplier's supply capacity and the production capacity of the manufacturing center are all certain values; the coordination of transportation products between the manufacturing centers does not affect the customer's needs. The location and number of the center are known; each customer only picks up one center for delivery, the reliable manufacturing center does not interrupt, the unreliable manufacturing center will interrupt with a certain probability, and some of the supply capacity will be lost when the interruption occurs, but which can be complemented by a reliable manufacturing center.

2.2. Symbols and Meanings

2.2.1. Collection Definition

I: reliable production center number, $i \in I$

J: unreliable manufacturing center number, $j \in J$

L: all manufacturing center numbers, $l \in L$ 且 $L \in (I \cup J)$

K: customer point number, $k \in K$

2.2.2. Parameter Definition

$\otimes d_k$: fuzzy demand for the kth customer

d_{ab}: transportation cost from manufacturing center a to manufacturing center b or customer

d_{pi}: unit transportation cost from supplier to reliable manufacturing center

d_{pj}: unit transportation cost from supplier to unreliable manufacturing center

γ_1: manufacturing center 1 distribution capacity

CR_i: start-up cost of a reliable manufacturing center

CR_j: the cost of starting an unreliable manufacturing center

qj: unreliable distribution center j

pj: loss ratio of capacity after unreliable distribution center j interruption

2.2.3. Decision Variables

U_i: supplier flow to manufacturing center i

U_j: supplier flow to manufacturing center j

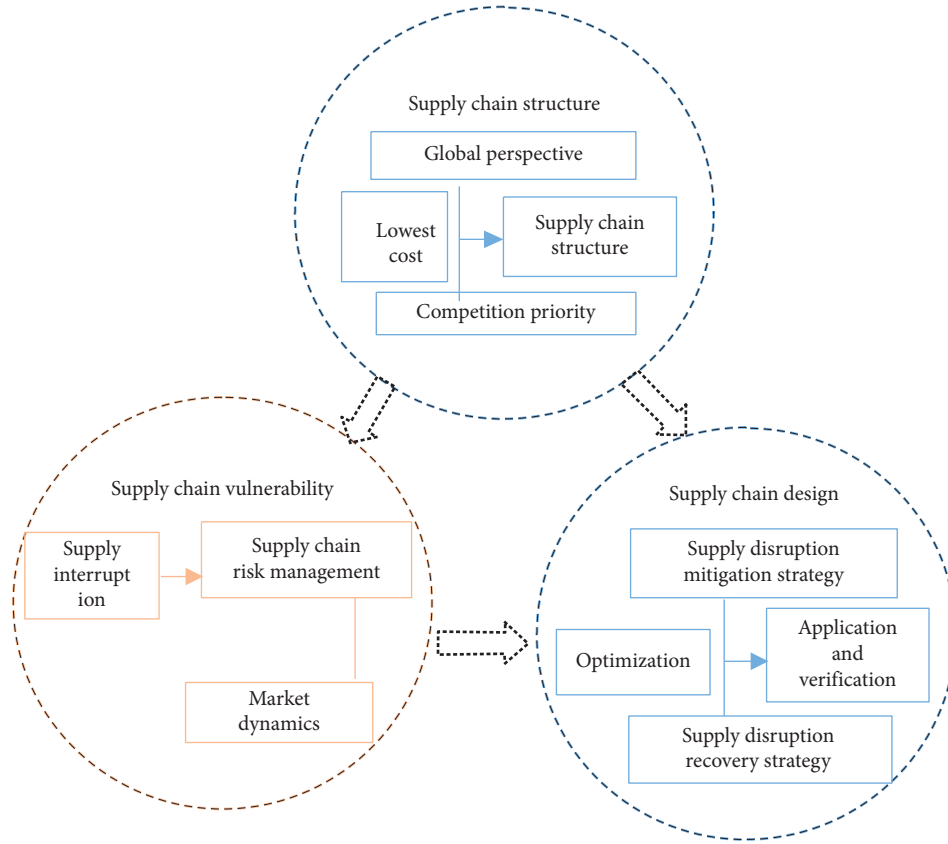FR_{ik}: reliable manufacturing center to customer k

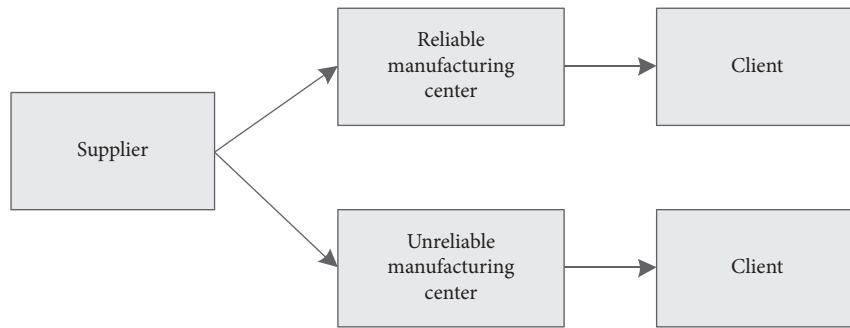FIGURE 1: Dynamically built supply chain flexibility concept map.

FIGURE 2: Three-level global supply chain network structure.

FU_{jk}: unreliable manufacturing center to customer k

T_{ij}: the number of deliveries from the reliable manufacturing center i to the unreliable manufacturing center j after the interruption occurred

YR_i: binary variable, 1 means reliable manufacturing center open; otherwise, 0

YU_j: binary variable, 1 means unreliable manufacturing center open; otherwise, 0

AR_{ik}: binary variable, 1 represents the customer assigned to a reliable manufacturing center; otherwise, 0

AU_{jk}: binary variable, 1 represents the customer assigned to the unreliable manufacturing center; otherwise, 0

2.3. Mathematical Modelling

$$\min \sum_i CR_i YR_i + \sum_j CU_j YU_j + \sum_i U_i d_{pi} + \sum_j U_j d_{pj}$$

$$+ \sum_i \sum_k \otimes d_k AR_{ik} d_{ik} + \sum_j \sum_k \otimes d_k AU_{jk} d_{jk} \qquad (1)$$

$$+ \sum_i \sum_j q_j T_{ij} d_{ij},$$

$$s.t. \ \sum_i AR_{ik} + \sum_j AU_{jk} = 1, \quad \forall k \in K, \qquad (2)$$

$$YR_l + YU_l \leq 1, \quad \forall l \in L, \qquad (3)$$

$$\sum_i YR_i \ge 1, \tag{4}$$

$$AR_{ik} \le YR_i, \tag{5}$$

$$AU_{jk} \le YU_j, \tag{6}$$

$$\sum_j FU_{jk} \bullet AU_{jk} \le T_{ij} + (1 - p_j) \bullet \gamma_j YU_j, \tag{7}$$

$$T_{ij} + (1 - p_j) \bullet \gamma_j YU_j \le \gamma_j YU_j, \tag{8}$$

$$\sum_k FU_{jk} \bullet AU_{jk} \ge \sum_k \otimes d_k \bullet AU_{jk}, \tag{9}$$

$$\sum_k FU_{ik} \bullet AU_{ik} \ge \sum_k \otimes d_k \bullet AU_{ik}, \tag{10}$$

$$YR_i, YU_j, AR_{ik}, AU_{jk} \in \{0, 1\}. \tag{11}$$

Among them, formula (1) is an objective function, which indicates the start-up cost of the manufacturing center, the transportation cost between the facilities, and the transshipment cost from the reliable manufacturing center to the unreliable manufacturing center, with the goal of minimizing the total cost. The constraint condition (2) indicates that a customer can only be assigned to one manufacturing center to meet the demand; formula (3) indicates that only one reliable manufacturing center or unreliable manufacturing center can be constructed at one location; and (4) indicates at least one reliable manufacturing center; formulas (5) and (6) indicates that the customer is assigned to a reliable manufacturing center or an unreliable manufacturing center; formulas (7) and (8) indicate that the flow rate of the material flowing out in the unreliable distribution center is not greater than the sum of the inflow amount and the amount of the inflow. And, less than its production capacity, equations (9) and (10) indicate that customer requirements should all be satisfied; equation (11) represents the value range constraint of the control variables.

2.4. Conversion of Fuzzy Constraints. The objective function in the above model contains uncertain parameters, and it is difficult to solve. Therefore, according to the random chance-constrained programming method in the uncertainty theory proposed by Liu and its followers [46, 47], the fuzzy number model with the customer's uncertain demand is transformed into a deterministic model. The fuzzy demand for the customer $\otimes d_k$ is expressed as a triangular fuzzy number (d_{j1}, d_{j2}, d_{j3}). The customer demand function $\mu_{\otimes d_k}(x)$ can be expressed as

$$\mu_{\otimes d_k}(x) = \begin{cases} \dfrac{x - d_{j1}}{d_{j2} - d_{j1}}, & \text{when } d_{j1} \le x \le d_{j2}, \\[2ex] \dfrac{x - d_{j3}}{d_{j2} - d_{j3}}, & \text{when } d_{j2} \le x \le d_{j3}, \\[2ex] 0, & \text{otherwise.} \end{cases} \tag{12}$$

For a given confidence level θ ($0 \le \theta \le 1$), according to the equivalence theorem in the stochastic chance-constrained programming, d_k can be obtained if and only if the following conditions are met:

$$\begin{cases} d_k \ge (1 - \theta)d_{j1} + \theta d_{j2}, \\ d_k \le (1 - \theta)d_{j2} + \theta d_{j3}. \end{cases} \tag{13}$$

3. Case Analysis

For an electronic product manufacturing enterprise, due to business development needs, the manufacturing center is deployed in the world for the production of electronic products. The manufacturing center is divided into two categories. One is a reliable manufacturing center, which is invested by itself. The production capacity of the manufacturing center will not be interrupted because of the uncertainty of demand and the output produced by it is stable. The other type is entrusted to other enterprises to process. This category is an unreliable manufacturing center. The production capacity of the manufacturing center will be adjusted due to the interests of the processing enterprise itself. Suppose that there is one supplier, four manufacturing centers (including reliable manufacturing centers and unreliable manufacturing centers), and six end customers. The confidence level of customer demand uncertainty is $\theta = 0.8$, assuming an outage probability of 0.15, and the capacity loss ratio of an unreliable manufacturing center is 0.3. The other parameters are listed in Table 1.

Substitute the parameters into the model and solve them with MATLAB software. The results are shown in Table 2.

As can be seen from Table 2, the objective function is 115,586 yuan, of which the manufacturing center with the opening numbers 1, 3, and 4 is a reliable manufacturing center invested and built by electronic product manufacturing enterprises, and the manufacturing center numbered 2 is entrusted to other enterprises for processing by electronic product manufacturing enterprises, which is an unreliable manufacturing center. The total cost of starting a reliable manufacturing center and an unreliable manufacturing center is 102,139 yuan, the transportation cost is 13,397 yuan, and the transportation cost is 65 yuan. The transfer volume of the reliable manufacturing center 3 to

TABLE 1: Partial parameter range table.

Parameter	Range	Parameter	Range
γ_i	Uniform (300, 520)	CU_j	Uniform (18000, 26000)
θ	0.8	CR_i	Uniform (21600, 31200)
d_{ab}	(1, 6, 11)	—	—

TABLE 2: Results of the study.

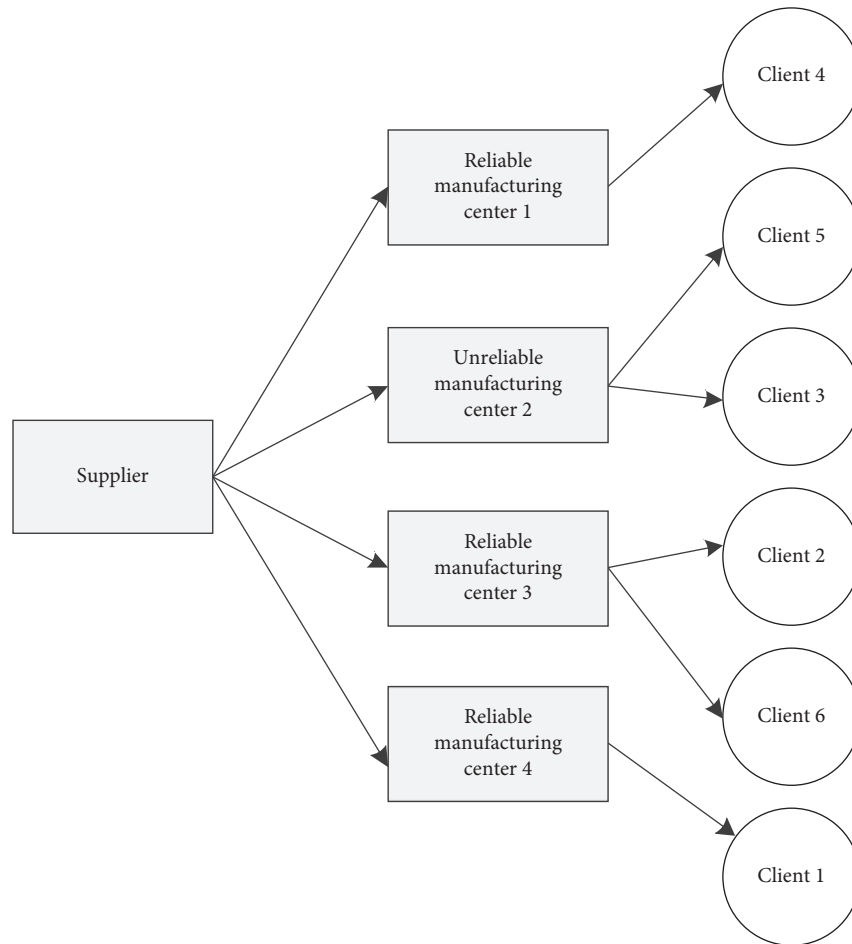| Objective function value	Manufacturing center cost	Transportation cost	Transshipment cost	YR_i	YU_i
115,585	102,139	13,381	65	1, 3, 4	2

FIGURE 3: Intersite logistics transfer map.

the unreliable manufacturing center 2 is 56.3, as shown in Figure 3.

Electronic manufacturing companies choose to invest in building manufacturing centers or entrust other foundry companies to make decisions between processing products. When entrusting other processing enterprises to OEM, they will face the interests of other foundry companies, there is a risk of supply interruption, resulting in loss of processing capacity, and the products cannot be delivered on schedule. In order to better analyze the relationship between capacity loss parameters and product cost expenditure, sensitivity analysis of capacity loss and results is performed. The

location and quantity of the manufacturing center are determined by changing the capacity loss rate of the unreliable manufacturing center. The total cost, transportation cost, transportation cost, and transshipment amount in the objective function are shown in Table 3.

In the case of overcapacity, the manufacturing center will face the loss of processing capacity. In the face of customer demand uncertainty, the grey theory is used to change the uncertainty problem into the uncertainty probability problem, the transshipment strategy is used to supplement the capacity of unreliable manufacturing center, a three-level supply chain model is established to simulate the market

TABLE 3: Sensitivity analysis of capacity loss.

| Number	Loss of capacity	Total cost	Central cost	Transportation cost	Transshipment cost	YR_i	YU_i
1	0.1	138071.3	123134.6	14924.04	12.66	4	1, 2, 3
2	0.15	138090.2	123134.6	14924.04	31.56	4	1, 2, 3
3	0.2	137975.5	123134.6	14782.23	58.67	4	1, 2, 3
4	0.25	138011	123134.6	14782.23	94.17	4	1, 2, 3
5	0.3	138054.8	123134.6	14782.23	137.97	4	1, 2, 3
6	0.35	138097.7	123134.6	14782.23	180.87	4	1, 2, 3
7	0.4	176405.9	162413	13752.93	239.97	2, 4	1, 3
8	0.45	176453.5	162413	13752.93	287.57	2, 4	1, 3
9	0.5	176241.5	162413	13467.33	361.17	2, 4	1, 3
10	0.55	176130.7	162413	13302.41	415.29	2, 4	1, 3
11	0.6	182986.7	169158.2	13302.41	526.1317	1, 2	3, 4
12	0.65	216218.8	201436.6	14782.2	0	1, 2, 3	—
13	0.7	216218.8	201436.6	14782.2	0	1, 2, 3	—
14	0.75	216218.8	201436.6	14782.2	0	1, 2, 3	—
15	0.8	216218.8	201436.6	14782.2	0	1, 2, 3	—
16	0.85	216218.8	201436.6	14782.2	0	1, 2, 3	—
17	0.9	216218.8	201436.6	14782.2	0	1, 2, 3	—
18	0.95	216218.8	201436.6	14782.2	0	1, 2, 3	—
19	1	216218.8	201436.6	14782.2	0	1, 2, 3	—
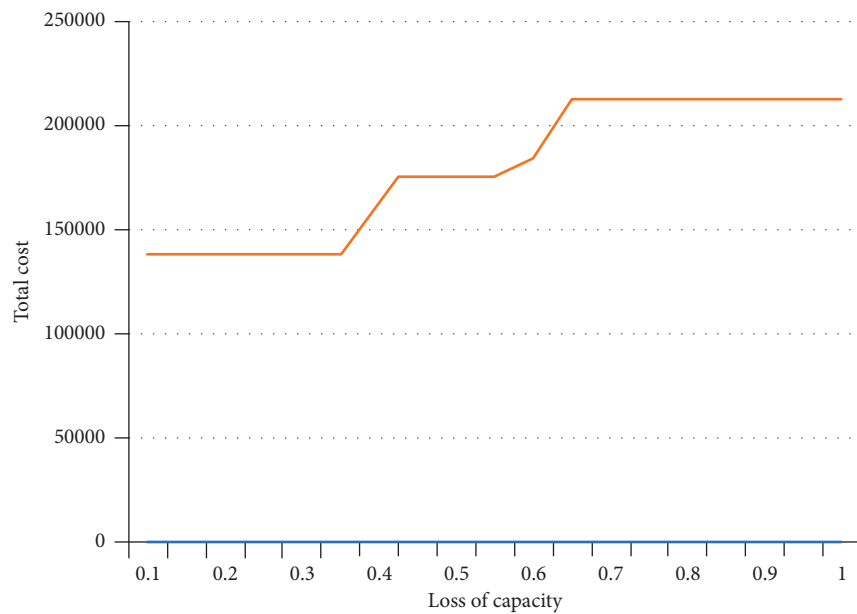
FIGURE 4: Total cost versus loss of capacity.

operation rules, and the sensitivity analysis of capacity loss to uncertain market demand is conducted. It is found that the greater the capacity loss of unreliable manufacturing center is, it is impossible that the total cost of supply chain and transportation shows an upward trend due to the insufficient operating rate of manufacturing centers. When the capacity loss reaches a certain degree, the manufacturing center with the lowest production capacity will be eliminated, and the overall cost is on the rise.

From the numerical results in columns 2 and 3 of Table 3, it can be concluded that when the capacity loss rate of modern industrial enterprises increases, the total cost of the supply chain shows an upward trend, and the manufacturing center also changes to a reliable manufacturing center (as shown in Figure 4). When the capacity loss reaches 0.65 and above, all manufacturing centers would have been converted into reliable manufacturing centers, and production centers with backward production capacity would have been discontinued.

In order to form the core competitiveness of manufacturing enterprises, it is suggested to develop reliable manufacturing centers as far as possible to cope with the uncertainty of market demand. If the market-oriented OEM manufacturing enterprises can save the construction and management costs of manufacturing centers, the stability of product manufacturing cannot be guaranteed, which may

cause supply interruption. Therefore, manufacturing enterprises need to build reliable manufacturing centers to ensure the flexibility of the supply chain.

4. Conclusions

This paper studies the problem of supply chain disruption in the downstream chain of manufacturing enterprises due to product foundry. The deep reason is that, in the face of risk decision-making, manufacturers will make decisions according to their own interests. This conflict between the manufacturer's interests and the supply chain's interests leads to the risk of disruption, which is more common in daily supply chain operations. When manufacturing companies face the risk of supply disruption, they will not only cause lost production capacity but also even lead to continuous business interruption. In order to solve the downstream supply disruption crisis of manufacturers under uncertain demand, this paper analyses the market elimination mechanism under the condition of product OEM production by constructing the global supply chain of three-level manufacturing enterprises and gives the supply chain elasticity optimization response strategy of manufacturing enterprises. The study found that the development of reliable manufacturing centers can effectively deal with the uncertainty of market demand, while market-oriented product OEMs can save the construction and management costs of manufacturing centers, but the stability of product supply is not stable. To the guarantee, it is likely to cause the risk of supply disruption. Therefore, in order to form the core competitiveness of manufacturing enterprises, the manufacturing supply chain design needs to flexibly select reliable manufacturing centers and unreliable manufacturing centers, reduce the total cost of the supply chain, and ensure the stable operation of the supply chain. In the complex market competition environment, manufacturing enterprises should actively respond, including the supply chain design and the recovery strategy plan after the interruption, so as to form a flexible global supply chain with more risk resistance and improve market competitiveness.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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