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CONSTRUCTION OF SUPPLY CHAIN COORDINATION AND OPTIMIZATION MODEL OF FRESH FOOD E-COMMERCE PLATFORM BASED ON IMPROVED BACTERIAL FORAGING ALGORITHM

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Abstract. In order to maximize the overall profit of the supply chain of fresh food e-commerce platform, the supply chain coordination and optimization model of fresh food e-commerce platform based on the improved bacterial foraging algorithm is constructed. The basic model of bacterial foraging algorithm is constructed through chemotaxis, reproduction, elimination & dispersal, and the bacterial foraging algorithm is improved by using four parts: bacterial individual and parameter initialization, chemotaxis behavior, reproduction behavior and migration behavior, so as to realize the coordination and optimization of the supply chain of fresh food e-commerce platform. Use the Internet service platform to promote the electronization of the supply chain transaction process and improve the overall operation efficiency. Through the cooperation among fresh food suppliers, fresh food e-commerce and upstream fresh food suppliers, the supply chain coordination and optimization model of fresh food e-commerce platform is constructed to improve the overall profit of the supply chain. The experimental results show that using the improved bacterial foraging algorithm to solve the supply chain coordination and optimization model of fresh food e-commerce platform has high effectiveness, and can maximize the overall profit of the supply chain of fresh food e-commerce platform.

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1. Introduction

Social and economic development has promoted consumers' demand for fresh products, and the demand for fresh products has gradually changed from quantity demand to quality pursuit, which has promoted the supply chain development of fresh food e-commerce platform to a certain extent [28]. The quality of fresh products is greatly affected by environmental factors. Consumers have the pursuit of timeliness and personalization for product distribution. Fresh food e-commerce is particularly critical for product quality control and logistics service management. Quality control and logistics service management will increase the cost input and indirectly affect the revenue of the supply chain. In the operation of the supply chain, fresh food e-commerce enterprises have the absolute dominant power [23], downstream e-commerce enterprises can obtain greater benefits in

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the operation process, while upstream fresh food suppliers obtain relatively less benefits, which reduces the enthusiasm of participating in cooperation to a certain extent.

In the operation process of supply chain of fresh food e-commerce, how to protect the interests of supply chain members of fresh food e-commerce on the premise of meeting consumer demand is the key to the supply chain coordination of fresh food e-commerce platform [29]. Since 2011, e-commerce for fresh products has sprung up rapidly, and different types of fresh food e-commerce platforms such as Tmall, Jingdong and Shunfeng have sprung up. In order to stimulate consumers' demand for fresh food e-commerce, fresh food e-commerce put forward a variety of promotional activities, such as 616 fresh Carnival of Suning Tesco, spring fresh festival of Tuotuo industrial society, warm Christmas of daily excellent fresh, etc. With the development of fresh food e-commerce, there is also a cold chain distribution system. In order to ensure that consumers can eat fresh and healthy fresh products [7, 11, 22], Suning supermarket proposed 24-hour delivery, Jingdong cold chain logistics provided full cold chain service, and daily excellent fresh products proposed 2-hour express delivery, aiming to meet consumers' demand for the quality of fresh products. The traditional distribution method can not meet the requirements of fresh products distribution. Based on the long-term development of fresh food e-commerce, it is very important to build a fresh cold chain distribution system to improve the level of fresh products preservation.

When consumers purchase fresh products on the fresh food e-commerce platform, in addition to the impact of product promotion activities, more and more consumers pay attention to the quality of fresh products after receiving [14], and the level of preservation efforts has also become an important factor affecting consumers' fresh demand. Yang *et al.* [30] found that the logistics service efforts of logistics service providers can improve the fresh-keeping level of fresh products and reduce the transportation loss of fresh products in transit, but at the same time of reducing costs, the distribution efficiency is low; Wu *et al.* [24] studied the logistics outsourcing contract between fresh food suppliers and third-party logistics (TPL) providers, and concluded that the fresh-keeping level affects the final product quality of fresh products, however, the quality of fresh products cannot be guaranteed when reducing costs; Xu *et al.* [26] concluded that the fresh-keeping service providers could improve the fresh-keeping level of fresh products when they studied the fresh house distribution mode. The input of in transit fresh-keeping will affect the freshness of fresh products, and then affect consumers' second purchase intention, however, it increases the distribution cost while ensuring the product quality. Mahata and Debnath [13] studied a single-item two-level supply chain inventory model, taking into account the deterioration of spoiled items during transport from the supplier's warehouse to the retailer's warehouse and the spoilage in the retailer's warehouse. The model can prevent the spoilage rate and maximize the profit per unit time of the retailer, but the model cannot guarantee the quality of fresh products; Saha *et al.* [21] proposed a multi-attribute decision-making method using the q-rung-orthopair fuzzy weighted fair aggregation operator. Some new neutral or fair operation rules are defined, and q-rung-orthopair fuzzy weighted fair aggregation operator (QROFFA) and q-Run-orthopair fuzzy ordered weighted fair aggregation operator (QROFOFFA) are developed, which can be neutral or fair to serve both membership and non-membership. However, the multi-attribute decision-making efficiency of this method is low; Debnath *et al.* [4] proposed a FEPQ model for sustainable projects with time and inventory-dependent needs under trade credit policies, considering the cost of phase-out and carbon emissions, and the proposed fuzzy inventory model was solved by the generalized Hukuhara derivative method. The model has some validity but does not take into account the quality of the product; Debnath *et al.* [5] introduced the concept of fuzzy differential equations, established a sustainable fuzzy economic production quantity inventory model, and applied the generalized Hukuhara differentiability process to solve the fuzzy differential equations. A reduction method based on the first critical value is applied to the demand function, which is transformed into a type 1 fuzzy variable. Finally, a multi-objective genetic algorithm is used to solve the nonlinear objective function, and the numerical and graphical sensitivity analysis of various parameters is carried out. But the cost involved in this model is higher; Debnath *et al.* [1] studied nonlinear fragility in two-warehouse inventory control for inventory-related demand, and also proposed two warehouse inventory strategies with continuous release patterns and two-level credit periods for suppliers and retailers. The study maximizes profits and thus minimizes total inventory costs. But the model runs less efficiently; Debnath *et al.* [2] built an inventory model using type 2 fuzzy parameters and solved it using the generalized Hukuhara derivative method. A first critical value (CV) based reduction method is applied to reduce the corresponding pentagon type 1 fuzzy variables. The model is able to find the optimal time to minimize the total inventory cost. However, the quality of stock products cannot be guaranteed.

In the fresh food e-commerce supply chain composed of fresh food e-commerce platform and suppliers, the improvement of effort level needs to pay the corresponding effort cost, which leads to the increase of the total cost of the supply chain [10, 17, 18]. Wang Lei *et al.* used wholesale price contract to help member enterprises improve the level of fresh-keeping efforts when they studied the limited capacity of fresh-keeping service of individual member enterprises in fresh agricultural products supply chain; Sana studied the effect of promotion efforts on supply chain channel coordination under uncertain market demand, and the conclusion showed that the market demand was affected by both promotion efforts and random variables, and the effect of promotion effort was not infinite increasing; Cachon *et al.* pointed out that revenue sharing contract could encourage member enterprises to make decisions in the direction of maximizing the total profit of the supply chain; Ma *et al.* studied the service effort problem of two-level supply chain, and concluded that only when cost sharing contract was considered in the contract could supply chain achieve perfect coordination.

The bacterial foraging algorithm was proposed by Kevin M. Passino in 2002, it can simulate the foraging behavior of Escherichia coli in human intestine. The three main behaviors in the life cycle of E. coli are chemotaxis, reproduction and elimination & dispersal. Bacterial foraging algorithm is composed of three nested cycles: The death & dispersion in cycle the outer layer, the replication cycle in the middle layer and the chemotaxis cycle in the inner layer [25]. Due to its complex structure and lack of information exchange mechanism, the standard bacterial foraging algorithm has the characteristics of slow convergence speed and low search accuracy. How to design the improved mechanism of the algorithm to make it have better performance is a hot topic in recent years.

Based on the above problems, a supply chain coordination and optimization model of fresh food e-commerce platform based on improved bacterial foraging algorithm is proposed. Using the improved bacterial foraging algorithm, a supply chain coordination and optimization model of fresh food e-commerce platform is established, which improves the working level and efficiency of the supply chain of fresh food e-commerce platform. Through the interaction of fresh food suppliers, fresh food e-commerce and upstream fresh food suppliers, the optimal pricing of fresh products is reduced, and the overall profit of the supply chain of fresh food e-commerce platform is maximized.

2. Model solving of improved bacterial foraging algorithm

2.1. Main steps of bacterial foraging algorithm

Bacterial foraging algorithm is a new kind of bionic algorithm which imitates the behavior of E. coli phagocytizing food in human intestine. In BFO algorithm, a bacterium represents a solution, and it only depends on itself to find the optimal solution. BFO has been widely used in many engineering and scientific fields because of its simplicity and efficiency. Passino's bacterial foraging algorithm consists of three steps: Chemotaxis, replication and death & dispersal.

(1) Chemotaxis

This process simulates the movement behavior of Escherichia coli flipping and swimming through flagella. When bacteria get a new movement direction through flipping, if bacteria can get more nutrition in this direction [19], bacteria will continue to swim in this direction; if bacteria get less nutrition in this direction than before, bacteria will flip.

Let $\theta^i(j,k,l)$ represent the position of the i bacteria after the j chemotaxis, k replication and l death & dispersal. In each chemotaxis, the movement of bacteria can be expressed by the following equation:

$$\theta^i(j+1,k,l) = \theta^i(j,k,l) + c(i)\frac{\Delta(i)}{\sqrt{\Delta^T(i)\Delta(i)}}. \tag{1}$$

In equation (1), $c(i)$ represents the chemotactic step size (unit operation step size) in any selected direction; Δ represents a random direction vector with the range of $[-1, 1]$.

After the bacteria update its position, the bacteria use the evaluation function to calculate its fitness value $J(i, j, k, l)$.

(2) Reproduction

The health status of each bacterium is expressed by the sum of the fitness values obtained by each chemotactic step, i.e. $\sum_{j=1}^{N_c} J(i, j, k, l)$. All bacteria are sorted according to the size of the sum of each fitness value. $S_r = S/2$ bacteria with poor health will all die, and the remaining excellent bacteria will replicate [20], so as to maintain the stability of bacterial population size. It is beneficial to improve the quality of bacterial population and speed up the optimization by eliminating the inferior individuals and retaining the excellent individuals.

(3) Elimination & dispersal

This step simulates the death or dispersal of bacteria due to environmental changes. The living environment of bacteria may change suddenly or slowly for a long time, such as the sudden rise of temperature and the gradual decrease of food, which will cause a certain number of bacteria to die or be forced to disperse to other areas. After N_{re} replications, the bacteria perform the death & dispersal step. In this step, a given probability p_{ed} is used to determine whether the bacteria will die and disperse. Bacteria meet this requirement and will be dispersed to any position in the optimization area [6]. The possibility of bacteria falling into local solution can be reduced by death & migration operation.

2.2. Improved bacterial foraging algorithm

The improved bacterial foraging algorithm is used to solve the supply chain coordination and optimization model of fresh food e-commerce platform. In order to better explain the improved bacterial foraging algorithm, some symbols are explained: S is the number of bacterial individuals in the population, N_{iter} is the evolution algebra, N_c is the chemotaxis times, N_s is the swimming times, N_{re} is the breeding times, N_{ed} is the migration times, P_{ed} is the migration probability. j. k, l and n are the counters of chemotaxis, reproduction, migration and evolution respectively.

The flow of the improved bacterial foraging algorithm is as follows:

(1) Individual and parameter initialization of bacteria

The individual position of the bacterial population is initialized and parameters N_{iter}, N_c, N_s, N_{re} and N_{ed} are also initialized. The distribution of the initial position of fresh supply is called a position of bacteria, and the position of the i bacteria is $\theta^i(j, k, l)$when it carries out the j chemotaxis, k reproduction and l migration.

(2) Chemotactic behavior

For all bacteria in the population, chemotaxis includes two behaviors: Turning and swimming.

First, the fitness $J\big(\theta^i(j, k, l)\big)$ of each bacteria is calculated, and the bacteria with the highest fitness value is selected as the global θ_{gbest}. θ^i_{lbest} is the local optimal position in the i bacterial chemotaxis process. For the first chemotaxis operation, a position is randomly selected in the coding matrix position and a direction $\varphi(i)$ is randomly selected ($[-2, -1, 1, 2]$ representing the four directions up, down, left and right), and the current position is updated by equation (2).

$$\theta^i(j + 1, k, l) = \theta^i(j, k, l) \otimes \varphi(i) \oplus c(i). \tag{2}$$

In equation (2), $c(i)$ represents the step size; the symbol $\otimes$ represents the direction selection; $\oplus$ represents to move $\varphi(i)$ from the current position of the matrix in the direction $\varphi(i)$ and transfer the number to column $c(i)$.

According to the equation (2), if the fitness value of current bacteria $\theta^i(j, k, l)$ is greater than θ^i_{lbest}, θ^i_{lbest} is updated and it swims along the current direction $\varphi(i)$; when it reaches the maximum number of swims N_s, it randomly selects a direction $\varphi(i)$ and adaptively selects the step size $c(i)$ to flip; if the fitness is not improved, it continues to flip until it is improved and turns to swim.

(3) Reproductive behavior

The bacteria that reach the critical number of chemotaxis complete a life cycle, and the survival of the fittest will be carried out according to the health evaluation. For the S bacteria individuals whose serial numbers are $1-S$, The health degree of the i bacteria is defined as [15]:

$$J_{health}^{i}=\sum_{j=1}^{N_C} J\big(\theta^{i}(j,k,l)\big), \quad i\in(1,2,\dots,S). \tag{3}$$

Equation (3) represents the cumulative sum of fitness of each bacterium in the population during chemotaxis. The health indicators of S bacteria are arranged in descending order, only half of the bacteria with higher health [27] are retained, and these bacteria are divided into two parts to keep the population size unchanged. At the same time, these new bacteria produced by replication had the same position as their parents.

(4) Migration behavior

In order to enhance the global optimization ability of bacteria and maintain the diversity of the population, all bacteria in the population will migrate to a random position in the solution space according to their own specified probability.

3. Construction of supply chain coordination optimization model for fresh e-commerce platform

3.1. Problem description and hypothesis

Supply chain e-commerce refers to the use of Internet service platform to realize the whole electronic process of supply chain transactions and completely change the traditional upstream and downstream business collaboration mode. Realize supply chain business collaboration, it can improve the information management of enterprises, and help enterprises quickly realize the comprehensive management and monitoring of information flow, capital flow and logistics through the platform [3]. At the same time, the use of supply chain e-commerce can make the supply chain upstream and downstream suppliers, enterprises, dealers, customers and other comprehensive business collaborative management, so as to achieve efficient capital turnover. Supply chain e-commerce can help enterprises change from traditional business mode to Internet era. With the in-depth application of Internet technology and the gradual formation of online trading habits, the business model of enterprises also needs to be changed accordingly. With the help of supply chain e-commerce platform, enterprises can share one-stop and all-round services from internal management to external business cooperation, thus liberating enterprise resources and significantly improving the productivity and operation efficiency of enterprises. Considering the fresh e-commerce supply chain composed of a single fresh e-commerce platform r and a single fresh supplier s, the fresh food suppliers are responsible for the production, primary processing and packaging of fresh products; the fresh food e-commerce platform is responsible for the sales of fresh products, and provides consumers with relevant online consulting and ordering services [8]. After consumers place orders successfully, the fresh food e-commerce platform's professional offline cold chain distribution service system completes the distribution service of fresh products.

The specific operation mode of supply chain of fresh food e-commerce platform is shown in Figure 1.

The unit cost of fresh products produced by fresh food suppliers is c_1, the unit wholesale price of fresh food e-commerce products obtained from fresh food suppliers is w, the unit sales price of fresh food e-commerce platform is p, and the unit cost of fresh food e-commerce platform for product distribution is c_2 by introducing promotion effort level and preservation effort level, the demand function of fresh products for consumers on fresh food e-commerce platform is expressed as follows [12]:

$$Q=a-bp+\alpha\theta_0 e_1+\beta e_2. \tag{4}$$

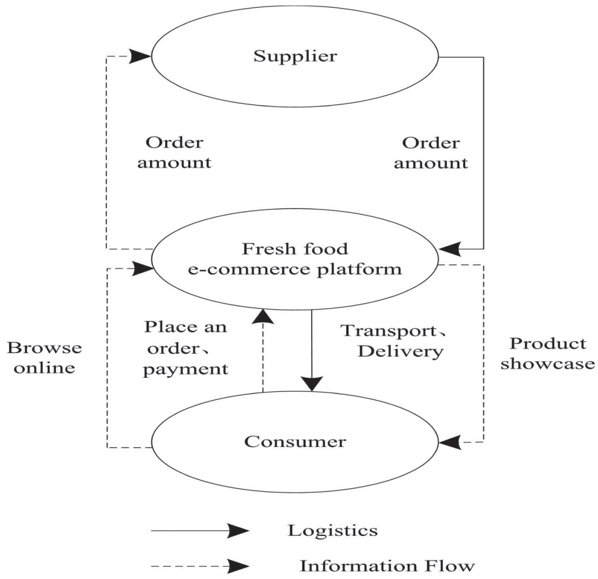

FIGURE 1. Supply chain operation mode of fresh food e-commerce platform.

That is to say, consumers' demand for e-commerce fresh products is affected by the sales price of fresh products p, in-transit preservation effort level e_1 and promotion effort level e_2. In the equation (4), $a(a > 0)$ is the potential e-commerce market environment demand of fresh products; $b(b > 0)$ is the price elasticity coefficient of demand Q; $e_1(e_1 > 0)$ is the preservation effort level; $\alpha(\alpha > 0)$ is the preservation effort level elasticity coefficient of demand Q; θ_0 is the freshness of fresh products before delivery; $e_2(e_2 > 0)$ is the promotion effort level; $\beta(\beta > 0)$ is the elasticity coefficient of promotion effort level of demand Q.

The functional relationship between preservation cost and preservation effort level is defined as follows [31]:

$$C(e_1) = \frac{1}{2}\lambda e_1^2. \tag{5}$$

In equation (5), $\lambda(\lambda > 0)$ is the cost coefficient of product preservation of e-commerce platform, and the larger the value is, the higher the cost of improving the same freshness is; $C(e_1)$ refers to the additional cost paid by the fresh food e-commerce platform for improving product preservation, refrigeration and other related logistics technology.

The functional relationship between promotion cost and promotion effort level is defined as:

$$C(e_2) = \frac{1}{2}\mu e_2^2. \tag{6}$$

In equation (6), $\mu(\mu > 0)$ is the promotion cost coefficient of the fresh food e-commerce platform, and the larger the value is, the higher the cost will be paid to improve the same promotion level; $C(e_2)$ refers to the promotion and publicity cost of the fresh food e-commerce platform, which has nothing to do with the basic operation cost of the fresh food e-commerce platform, but has something to do with the market demand Q.

The relevant parameter symbols are defined as follows:

Centralized decision-making mode: p_c is fresh product pricing, e_{c_1} is fresh keeping effort level, e_{c_2} is promotion effort level, π_c is total profit of fresh food e-commerce supply chain.

Decentralized decision-making model: p_{d_1} is fresh product pricing, w_1 is fresh product wholesale price, e_{d_1} is fresh keeping effort level, e_{d_2} is promotion effort level, π_{r_1} is fresh food e-commerce platform profit, π_{s_1} is fresh supplier profit.

After contract coordination: p_{d_2} is the pricing of fresh products, w is the wholesale price of fresh products, $e_{d_{11}}$ is the level of preservation efforts, $e_{d_{22}}$ is the level of promotion efforts, π_{r_2} is the profit of fresh food e-commerce platform, π_{s_2} is the profit of fresh food suppliers.

The assumption of the supply chain coordination and optimization model of fresh food e-commerce platform is as follows:

– Both parties are risk neutral and share all information;
– In order to ensure the profit of the member enterprises, the parameter should be $p > w + c_2 > c_1 + c_2$;
– Only considering the homogeneity of consumers, different consumers are affected by the same level of effort;
– The shortage loss of fresh products is not considered.

3.2. Supply chain coordination and optimization model of fresh food e-commerce platform

In order to make the optimal pricing and profit of fresh food e-commerce and fresh food suppliers meet the centralized decision, fresh food suppliers sell their products to fresh food e-commerce at a certain wholesale discount price. Fresh food e-commerce will reduce the product pricing, and share part of its platform revenue with upstream fresh food suppliers, so as to alleviate the impact of double marginal effect [9,16,32], and make the overall profit of the supply chain of fresh food e-commerce reach the optimal profit under medium decision. A revenue sharing contract (w_{t_1}, φ) is designed. The fresh supplier sells the fresh products to the fresh food e-commerce at the discount price $w_{t_1} < w_t$ $(w_{t_1} < w_t)$. After the current product sales, the fresh food e-commerce shares the sales revenue to the upstream fresh supplier according to the revenue proportion of $\varphi(\varphi \in (0,1))$. The fresh supplier and the fresh food e-commerce can share all the sales information. According to the revenue sharing contract, the profit functions of fresh food e-commerce and fresh supplier are as follows:

$$\pi_{tr_1} = (1-\varphi)d_t p_t - w_{t_1} d_t = (1-\varphi)Dp_t^{-k}\lambda\left(\frac{p_t}{p_{t-1}}\right)^{-r} p_t - w_{t_1} Dp_t^{-k}\lambda\left(\frac{p_t}{p_{t-1}}\right)^{-r}. \tag{7}$$

$$\begin{aligned}\pi_{ts_1} &= (w_{t_1} - c)d_t - \varphi p_t d_t \\ &= (w_{t_1} - c)Dp_t^{-k}\lambda\left(\frac{p_t}{p_{t-1}}\right)^{-r} + \varphi p_t Dp_t^{-k}\lambda\left(\frac{p_t}{p_{t-1}}\right)^{-r}.\end{aligned} \tag{8}$$

The optimal pricing of fresh food e-commerce platform is shown in Theorem 1.

Theorem 1. *Under the revenue sharing contract, for any fresh supplier's wholesale price w_{t_1} and revenue sharing ratio φ, the optimal pricing of fresh food e-commerce is as follows:*

$$p^*_{tr_1} = \frac{(k+r)w_{t_1}}{(k+r-1)(1-\varphi)}. \tag{9}$$

Proof. The fresh food supplier provides the retailer with the goods at the wholesale price, and obtains the $(1-\varphi)$ part of the profit of the fresh food e-commerce. φ determines the profit distribution of fresh food suppliers and fresh food e-commerce, and fresh food e-commerce determines the optimal pricing of fresh food e-commerce based on wholesale prices to maximize profits. □

Theorem 2. *When revenue sharing contract is adopted, if (w_{t_1}, φ) satisfies $w_{t_1} = c(1-\varphi)$ and $\frac{(k+r-1)^{k+r}}{(k+r)^{k+r}} < \varphi < 1 - \frac{(k+r-1)^{k+r-1}}{(k+r)^{k+r-1}}$, the supply chain of fresh food e-commerce can be coordinated.*

If the supply chain is coordinated, then $\frac{(k+r)w_{t_1}}{(k+r-1)(1-\varphi)} = \frac{c(k+r)}{k+r-1}$, then $w_{t_1} = c(1-\varphi)$ is obtained; if the fresh food e-commerce and fresh supplier accept the contract, the premise is that the profit after cooperation cannot be less than the profit of decentralized decision before cooperation, that is:

$$\begin{cases}\pi_{tr_1} > \pi_{tr} \\ \pi_{ts_1} > \pi_{ts}\end{cases}, \quad \frac{(k+r-1)^{k+r}}{(k+r)^{k+r}} < \varphi < 1 - \frac{(k+r-1)^{k+r-1}}{(k+r)^{k+r-1}}. \tag{10}$$

Table 1. Parameter assignment

Parameter	c_1	c_2	w_1	λ	μ	θ_0	α	β	a	b
Assignment	6	5	10	20	25	0.9	6	13	310	12

Proof. Fresh food e-commerce and fresh food suppliers jointly negotiate sales revenue, optimize resource allocation, ensure that the final profit obtained by both parties is higher than the profit of decentralized decision-making before cooperation, and achieve a win-win situation for fresh food e-commerce and fresh food suppliers. □

Theorem 2 shows that the design of reasonable revenue sharing contract can realize the coordination of fresh e-commerce supply chain, make fresh suppliers and fresh e-commerce profit, and achieve a win-win situation. Formula (10) shows that when the price elasticity coefficient is constant, with the increase of r, the value range of φ is also increasing, indicating that in the actual fresh e-commerce sales process, if consumers are more sensitive to the relative price of fresh products, or more consumers are more sensitive to the relative price of fresh products [33], under the revenue sharing contract cooperation, the higher the profit sharing ratio of fresh suppliers, to a certain extent, the cooperation between fresh suppliers and fresh e-commerce can be encouraged.

4. Results

In order to verify the effectiveness of the supply chain coordination optimization model of fresh food e-commerce platform in practical application, a regional fresh food e-commerce platform is selected as the experimental object. The experimental data are from a regional fresh food e-commerce platform, and the relevant parameters are set for verification. The fresh food e-commerce platform can standardize the fresh food processing process, integrate manual operation and electronic information, facilitate public business activities, and ensure network security management. Suppose that in the supply chain coordination and optimization model of fresh food e-commerce platform, Using Matlab 7.0 to calculate the indicators before and after the coordination between the supplier and the retailer during the joint replenishment period, the parameters are assigned as shown in Table 1.

In Table 1, $\lambda(\lambda > 0)$ is the cost coefficient of product preservation of e-commerce platform, $\beta(\beta > 0)$ is the elasticity coefficient of promotion effort level of demand Q. $a(a > 0)$ is the potential e-commerce market environment demand of fresh products; $b(b > 0)$ is the price elasticity coefficient of demand Q; $\alpha(\alpha > 0)$ is the preservation effort level elasticity coefficient of demand Q; θ_0 is the freshness of fresh products before delivery; $\mu(\mu > 0)$ is the promotion cost coefficient of the fresh food e-commerce platform, The unit cost of fresh products produced by fresh food suppliers is c_1 is the unit cost of fresh products produced by fresh food suppliers, c_2 is the unit cost of fresh food e-commerce platform for product distribution, w is the wholesale price of fresh products.

In order to test the performance of the improved bacterial foraging algorithm for solving the supply chain coordination and optimization model of fresh food e-commerce platform, the convergence index and diversity index are selected to measure the effectiveness of the solution.

The convergence index GD, also known as generation interval, is used to describe the interval between the non-inferior solution and the real optimal solution

$$GD=\frac{\sqrt{\sum_{i=1}^{n} \text{dist}_i^2}}{n}. \tag{11}$$

In equation (11), dist is the minimum Euclidean distance between a non-inferior solution and the optimal solution, and n is the number of samples. The smaller the convergence index is, the higher the convergence of the algorithm is.

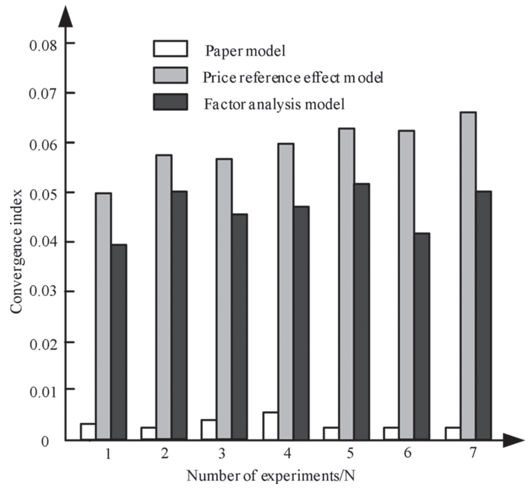

FIGURE 2. Comparison of convergence index.

The diversity index is used to calculate the inconsistency of distribution, that is, to measure the distribution of solutions

$$\Delta = \frac{h_l + h_f + \sum_{i=1}^{n-1} \left| h_i - \bar{h} \right|}{h_l + h_f + (n-1)\bar{h}}. \tag{12}$$

In equation (12), h_i represents the distance between adjacent solutions, $\bar{h}$ represents the average value of h_i, h_f and h_l represent the extreme distance and the current boundary solution individual distance respectively, and n represents the number of non-dominated solutions.

When the non-dominated solution is widely and evenly distributed, the diversity index value is 0. For any other distribution, the value of the index will be greater than 0. If the values of h_f and h_l of the two distributions are the same, it means that the distribution of solutions is poor in the range of limit solutions, and the index will have a larger value. Therefore, the diversity index can be used to measure the distribution of solutions. The smaller the diversity index is, the better the diversity and distribution of non-inferior solutions are.

This paper selects the price reference effect model and factor analysis model as the comparative model to verify the effectiveness of the improved bacterial foraging algorithm in solving the supply chain coordination and optimization of the fresh food e-commerce platform. The three models all set the same population size and the maximum number of iterations, which are 8,080,000. The convergence index and diversity index are calculated by different models for 7 times, and the comparison results are shown in Figures 2 and 3.

From the comparison results of Figures 2 and 3, when the number of experiments is 7, the average convergence index and diversity index of this model are 0.005 and 0.08 respectively, while the average convergence index and diversity index of price reference effect model are 0.06 and 0.5 respectively, and the average convergence index and diversity index of factor analysis model are 0.048 and 0.52, respectively. It can be seen that the improved bacterial foraging algorithm used in the model in this paper has strong solving performance, and the model in this paper can obtain better generation spacing under different experimental times, which indicates that the improved bacterial foraging algorithm used in this model is easier to converge. This model can obtain the optimal solution quickly and has strong convergence performance. This model also has strong performance in diversity, which shows that this model has better diversity index. Figures 2 and 3 effectively verify that the improved bacterial foraging algorithm used in this paper has strong overall performance. When the model is used to solve high-dimensional complex problems, it can achieve fast convergence, and it still has strong computational performance when solving multi-objective problems.

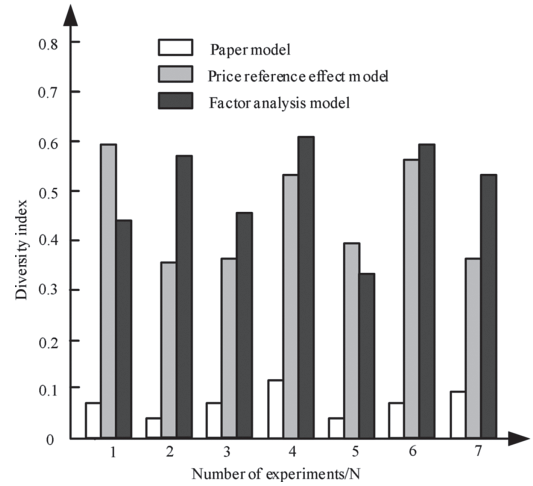

FIGURE 3. Comparison of diversity indicators.

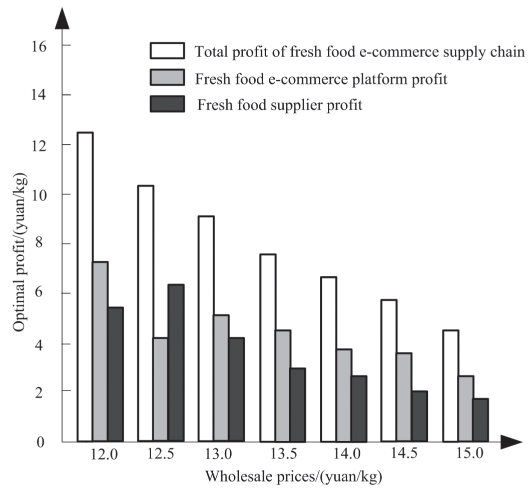

FIGURE 4. Changes in supply chain profits under different wholesale prices.

The model in this paper is used to calculate the profit changes of supply chain of fresh food e-commerce platform under different wholesale prices, as shown in Figure 4.

As can be seen from the experimental results in Figure 4, with the increase of the wholesale price of fresh products, the total profit of the supply chain of fresh food e-commerce platform, the profit of fresh food e-commerce platform and the profit of fresh food suppliers have decreased, which is consistent with the actual situation. When the wholesale price is 12 yuan/kg, all of them reach the maximum. When the wholesale price is 12 yuan/kg, the total profit of the supply chain of fresh food e-commerce platform is 12.34 yuan/kg. The change of wholesale price will lead to the change of price and demand, which indicates that the more price reference effect exists, the more cooperation should be carried out between fresh food suppliers and fresh food e-commerce to improve their profits.

When the effort level of online shopping consumers for the same commodity reference price is different, the optimal decision results obtained by the model in this paper are shown in Table 2.

TABLE 2. The optimal decision under the influence of different effort levels.

Effort level influence	Wholesale prices of fresh products/ (yuan/kg)	Fresh product pricing/(yuan/kg)	Fresh food supplier profit/(yuan/kg)	Fresh food e-commerce platform profit/(yuan/kg)	Total profit/(yuan/kg)
5	7.7561	12.7845	8.5215	9.5121	18.0336
6	7.7354	12.6845	8.9451	9.7512	18.6963
7	7.7054	12.5845	9.5125	10.2564	19.7689
8	7.6845	12.5268	9.8546	10.3541	20.2087
9	7.6584	12.4215	10.2542	10.5234	20.7776
10	7.6354	12.3546	10.5231	10.7512	21.2743
11	7.6154	12.2654	10.7851	10.9521	21.7372
12	7.5946	12.1542	11.2354	11.2558	22.4912
13	7.5864	12.0543	11.8542	11.5345	23.3887
14	7.5645	11.9456	12.2145	11.7516	23.9661
15	7.5468	11.8542	12.3451	11.9521	24.2972
16	7.5264	11.6854	12.5846	12.6452	25.2298
17	7.5165	11.6752	12.8654	12.9512	25.8166
18	7.4952	11.6524	13.2546	13.5486	26.8032
19	7.4856	11.5954	13.5648	14.2586	27.8234
20	7.4356	11.5864	13.8545	14.8456	28.7001
21	7.4251	11.5648	14.5231	15.7645	30.2876

According to the experimental results in Table 2, with the increase of effort level, the optimal wholesale price and optimal pricing of fresh food e-commerce are decreasing, but the profits of fresh wholesalers and fresh food e-commerce are increasing, and the overall profits of the supply chain are also increasing. With the increase of consumers' influence on the level of effort, due to the product price transparency of fresh food e-commerce platform, a little price fluctuation may cause a significant change in consumer demand, which means that the greater the reference effect is, the greater the impact on the profits of fresh food e-commerce and fresh food suppliers is. This paper analyzes the impact of price reference effect on the optimal pricing and profit of fresh food e-commerce platforms, establishes the revenue sharing contract between fresh food e-commerce platforms, ensures the supply chain coordination of fresh food e-commerce, and quantitatively solves the relationship between the parameters of supply chain coordination of fresh food e-commerce. Through numerical simulation, it is found that the optimal profit of centralized decision-making for the supply chain of fresh food e-commerce is greater than that of decentralized decision-making and the impact of wholesale price and reference effect on the profit and optimal pricing of fresh food suppliers and fresh food e-commerce is quantitatively analyzed. The contract increases the overall profit of supply chain of fresh food e-commerce, increases the profit of fresh food e-commerce and fresh food suppliers, and reduces the online sales price of products, so as to achieve a win–win situation on the basis of protecting the rights and interests of consumers.

Different models are used to optimize the supply chain of fresh food e-commerce platform with different fresh-keeping cost coefficients. The profit promotion results of fresh food suppliers and fresh food e-commerce platform are shown in Figures 5 and 6.

The comparison results of Figures 5 and 6 show that the benefits of both sides are increasing with the increase of preservation cost coefficient, which indicates that consumers have higher demand for fresh products with high freshness. When the freshness of fresh products is high, fresh food e-commerce platform can obtain higher income, which can promote the two sides to invest in fresh-keeping efforts. When the fresh-keeping cost coefficient is 0.9, the optimal profit of supplier and fresh food e-commerce platform of this model is 6.5 and 6.9 yuan/kg respectively, while the optimal profit of supplier and fresh food e-commerce platform of price reference

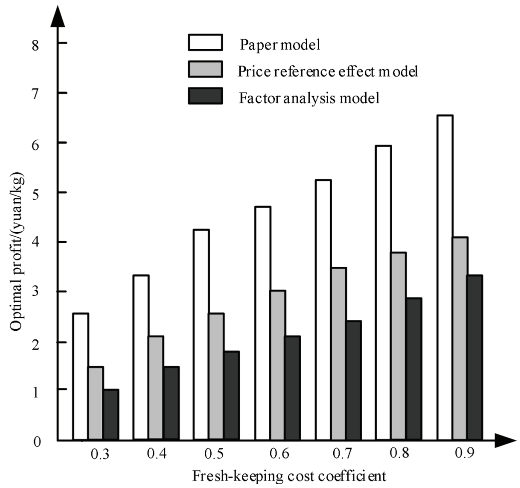

FIGURE 5. Changes in profit of fresh food suppliers.

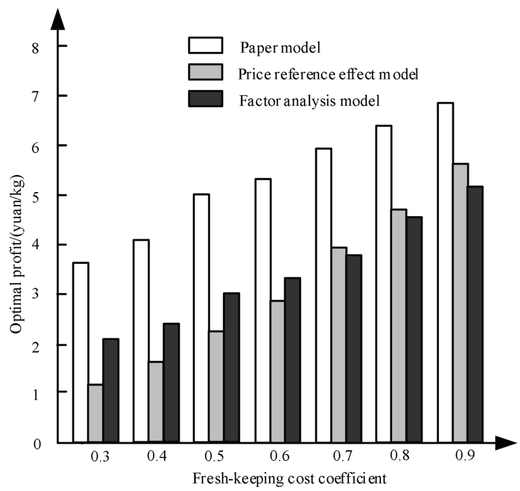

FIGURE 6. Changes in profits of fresh food e-commerce platforms.

effect model is 4 and 5.6 yuan/kg respectively, and the optimal profit of supplier and fresh food e-commerce platform of factor analysis model is 3.3 and 5.1 yuan/kg respectively. From this we can see that, the supply chain of fresh food e-commerce platform optimized by the proposed model has the optimal coordination effect under different fresh-keeping cost coefficients.

In order to verify the inhibitory effect of the incentive and restraint mechanism based on information sharing on the bullwhip effect, the order quantity of the two methods was tested during the 8-month order period, and the test results are shown in Figure 7.

It can be seen from Figure 7 that the order quantity is between 1.5 and $2t$ when the incentive and constraint mechanism of information sharing is not used. After using the incentive and restraint mechanism of information sharing, the order quantity is below $0.5t$, which is significantly lower than the order quantity when the incentive and restraint mechanism of information sharing is not used, which proves that the incentive and restraint mechanism based on information sharing can effectively suppress the bullwhip effect.

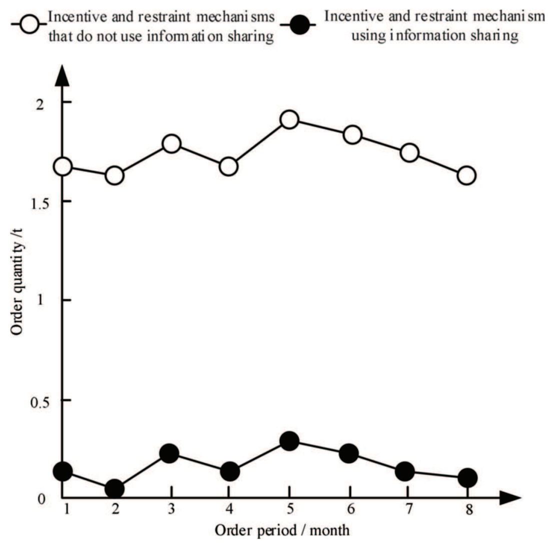

FIGURE 7. Inhibitory effect of information sharing-based incentive and restraint mechanism on bullwhip effect.

The supply chain of fresh food e-commerce platform optimized by the proposed model has higher profits under different insurance cost coefficients, and it effectively verifies that compared with the other two models, the supply chain coordination and optimization of fresh food e-commerce platform by using the proposed model has better effect.

5. Discussion

This paper constructs an supply chain coordination and optimization model of fresh food e-commerce platform based on improved bacterial foraging algorithm, and verifies through experiments that the established model can effectively improve the profit of fresh food e-commerce platform through supply chain coordination and optimization.

From the perspective of channel members' cooperation, considering the impact of freshness on demand, it is a new problem to study how to coordinate the supply chain of fresh food e-commerce platform. The necessity of supply chain coordination of fresh food e-commerce platform is as follows:

(1) It helps to improve the operation efficiency of fresh food supply chain

In the fresh food supply chain, both fresh food e-commerce and fresh food suppliers hope to maximize their own interests, which leads to the fact that in the actual operation of the supply chain, the upstream and downstream enterprises of the supply chain start from their own interests and ignore the overall interests of the supply chain. In order to improve their own profits, fresh food suppliers often increase the wholesale price of fresh products, which leads to the decline of fresh food e-commerce profits. Due to the lack of good cooperative relationship between upstream and downstream enterprises in the fresh food supply chain, problems such as product quality defects and high logistics cost often appear in the operation process of the supply chain, which greatly reduces the operation efficiency of the fresh food supply chain.

(2) It is helpful to improve the quality of fresh products and logistics service level

Through the coordination of fresh food e-commerce supply chain, it can integrate the resources of upstream and downstream enterprises in the fresh food supply chain, give full play to each other's advantages. Fresh food suppliers control the quality of products at the source, and fresh food e-commerce is responsible for the logistics distribution of fresh products, use its own good cold chain logistics system to ensure the quality of fresh products in the transportation process and meet the needs of consumers for logistics services, so as to improve consumer satisfaction with fresh products logistics services, and the overall profit level of fresh food supply chain.

In order to improve the supply chain coordination of fresh food e-commerce platform, the implementation strategy of supply chain coordination of fresh food e-commerce platform is studied as follows:

(1) Reasonable distribution and coordination of revenue increased by contract decision

One of the obstacles in the implementation process of fresh food e-commerce supply chain is that enterprise members at all stages feel that profits have not been distributed fairly and reasonably. The premise of cooperation is to establish a coordination and guarantee mechanism to meet the needs of upstream and downstream enterprises and reasonable distribution of profits. If the coordination mechanism can realize the information sharing and joint decision-making among enterprises, the supply chain coordination of fresh food e-commerce can be realized. Through the use of coordination contract, we can achieve two goals: One is to maximize the benefits of the whole supply chain without losing the interests of any party under the condition of fulfilling the contract; the other is to make suppliers and platforms obtain more profits than when there is no contract through reasonable contract coordination parameters, so as to achieve a win-win situation in the supply chain.

(2) Attachment of importance to the development of the relationship with fresh food suppliers

The application of e-commerce technology shortens the supply chain of fresh food e-commerce, and makes the relationship between fresh food suppliers and fresh food e-commerce platform closer. The establishment of a stable strategic relationship between the fresh food e-commerce platform and suppliers can improve the overall competitiveness of the supply chain, and realize the purpose of expanding the fresh market share and reducing the cost of the fresh food e-commerce platform. Cooperation with fresh food suppliers can improve the platform's understanding of the quality and cost of fresh products. Fresh food suppliers can determine the production volume of relevant products according to the relevant demand data of fresh food e-commerce. Fresh food e-commerce can supervise the production process of suppliers according to the data provided by fresh food suppliers, so as to realize the long-term cooperation between fresh food e-commerce platform and fresh food suppliers, so as to realize win–win on the basis of cooperation.

(3) Establishment of incentive and restraint mechanism based on information sharing

Reasonable incentive and constraint mechanism of information sharing of fresh food e-commerce supply chain can make fresh food e-commerce platform establish strategic partnership with fresh food suppliers, improve the degree of information sharing between fresh food e-commerce platform and fresh food suppliers, share the system risk of fresh food e-commerce supply chain, reduce the total cost of system operation, and inhibit the gradual amplification question of demand information's bullwhip effect. Through the information sharing of fresh food e-commerce supply chain, fresh food e-commerce enterprises can obtain higher value-added, but fresh food suppliers can not directly make profits. Therefore, in order to ensure the interests of suppliers and actively share product information, it must establish the corresponding reasonable incentive and constraint mechanism.

(1) Target incentive

As a complex community of interests, supply chain system has a common interest goal. The realization of the overall goal of the supply chain is conducive to the profit promotion of the member enterprises. Through the analysis of the actual operation situation and interest demands of fresh food e-commerce platform and fresh food suppliers in the supply chain, scientific and reasonable objectives are set, the overall objectives are linked with the interests of each member, and the goal setting is linked with the implementation, so as to stimulate the enthusiasm of each member enterprise to the greatest extent and maximize the overall profit of the supply chain.

(2) Restraint mechanism

As an independent individual, the e-commerce platform and suppliers in the fresh food e-commerce supply chain can hardly avoid using information asymmetry to increase their own interests and damage each other's interests in the process of normal production, operation and cooperation. In order to restrain this kind of behavior and punish the behavior, the fresh food e-commerce supply chain should establish an effective restraint mechanism. Once one party has speculative behavior, the other party immediately adopts the corresponding punishment mechanism. Through this mechanism, the behavior between the fresh food e-commerce platform and the fresh supplier can be regulated, which has a certain degree of supervision and management effect.

(3) Trust mechanism

The cooperative relationship between fresh food e-commerce platform and fresh food suppliers should be based on trust. Both sides should effectively implement the mechanism of rewarding trustworthy behavior and punishing speculative behavior. Fresh food e-commerce platform and fresh food suppliers should strive to improve their industry reputation, which can increase mutual trust to a certain extent. In order to establish an effective trust mechanism of supply chain, it is necessary to contact the economic interests of each member enterprise, make the business decisions of each enterprise open through information sharing, and promote the construction of trust mechanism.

6. Conclusions

Combined with the development status of fresh food supply chain in the e-commerce environment, the research on the supply chain coordination of fresh food e-commerce platform is carried out, and the supply chain coordination and optimization model of fresh food e-commerce platform is constructed based on the improved bacterial foraging algorithm. At present, the supply chain problems of fresh food e-commerce platform mainly focus on the conflict of interest among member enterprises, weak cold chain system in the transportation process, small coverage, poor terminal logistics service quality and other problems, which make the supply chain of fresh food e-commerce unable to operate reasonably and efficiently. Taking the coordination contract as a whole consideration, combined with the enterprise data for specific example analysis, relevant strategies are put forward for supply chain coordination. The results show that the improved bacterial foraging algorithm is effective in solving the supply chain coordination optimization model of fresh food e-commerce platform, which can maximize the overall profit of the supply chain of fresh food e-commerce platform, and improve the working level and efficiency of the supply chain of fresh food e-commerce platform. The total profit of the supply chain of fresh food e-commerce is affected by the level of preservation effort and promotion effort. With the increase of elasticity coefficient, the profit of the supply chain system of fresh food e-commerce platform as a whole and cooperative enterprise is increasing. In this model, the freshness of the product is fixed, the product cost is fixed, and the production cost, transportation cost and inventory holding cost are not considered in detail. In the process of online sales, the product packaging cost and cold chain transportation cost are also not considered. Next, we should consider the problem of product pricing and supply chain coordination when the product freshness changes with time, including packaging cost and cold chain transportation cost. Therefore, future research work can focus on reducing product losses and transportation costs, improving logistics and transportation efficiency while controlling product quality, so as to improve operating profits.

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

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