Research On Optimal Planting Strategy of Crops Based on Nonlinear Programming and Monte Carlo Optimization Simulation

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Abstract. This article addresses the issue of crop planting conditions and optimal planting plans, using a nonlinear programming method based on Monte Carlo optimization, visualization processing, sensitivity analysis, and Pearson correlation coefficient analysis. The relationship between the optimal planting plan and various influencing factors such as planting land, crop name, crop type, planting area, and sales unit price is obtained, as well as how to determine the optimal planting plan (i.e. maximum revenue). It is required to find the optimal planting plan for two different sales situations within the limited area of four plots and two greenhouses, as well as various restrictions such as the inability to plant continuously on the same plot and the need to plant different types of crops on different plots. Firstly, preprocess the data to calculate the sales unit price based on the median, and in order to make reasonable use of land resources, multiple types of land can be used on one site; Secondly, using nonlinear programming methods, the restrictive conditions are processed and transformed into mathematical equations, and the rules are summarized and visualized through a lingo processor for analysis; Finally, using the objective function and the optimal planting plan provided by the lingo processor, the maximum profit under two different sales scenarios is obtained, which is denoted as yuan.

Keywords: Nonlinear programming model, Monte Carlo optimization, Sensitivity analysis, Planting strategy planning, Maximum revenue.

1. Introduction

According to the report of the 20th National Congress of the Communist Party of China, to accelerate the building of a strong agricultural country, " for China to be strong, its agriculture must be strong." As of 2023, the area of cultivated land for grain production was the largest, the area of cultivated land for vegetables ranks second. Meanwhile, China's grain output has increased from 639648300 tons in 2014 to 659410000 tons in 2023. Vegetable output rose from 631.98 million tons in 2014 to 799.9722 million tons in 2023, achieving a new breakthrough in agricultural output.

However, in recent years, extreme weather has occurred frequently, and diseases and pests have been rampant. The agricultural situation is complex and severe, and agricultural production is not optimistic. Many domestic scholars have conducted research on this. Scholars such as Leng have pointed out that the unit output of grain and vegetables (i.e., total output divided by cultivated land area) in China has shown a downward trend in the past decade[1], which indicates that there are still drawbacks in the rational utilization of land resources in China.

Under the condition of limited cultivated land area, increasing the unit output of agricultural production is of great significance for a country with a large population base like China. Therefore, how to make full use of the limited cultivated land area, increase the unit yield of agricultural production, and how to establish an accurate model to predict the optimal planting plan in the future is an important issue.

This paper mainly uses the nonlinear programming method based on Monte Carlo optimization to predict the best planting scheme in the future. In previous scholars' research, although there were ideas reflecting nonlinearity, most of them ignored the complex variables existing in reality in order to simplify the model. Based on their shortcomings, our research is conducted in three levels, gradually increasing the constraints to strive for a final result that is closer to the actual situation. The Monte Carlo method we have chosen is particularly suitable for probability modeling and uncertainty analysis of complex systems. In the first stage, we will first tally the specific data for 2023, convert some basic constraints into mathematical equations, and combine the objective function to determine the maximum profit under two different sales scenarios in the future. In the second stage, the influence of uncertain factors is taken into additional consideration, and the optimal planting plan is provided only for the two specific crops of wheat and corn. In the third stage, the correlations between sales volume and cost, output, etc. were taken into consideration. Combined with the previous restrictive conditions and uncertain factors, the objective function was improved, and finally a complete optimal planting plan was obtained.

2. Research on Maximum Crop Profit Based on Nonlinear Programming

In this chapter, we will sort out and analyze the specific data of cultivation and sales in 2023 (such as crop type, crop name, planting area, planting season, plot type, yield per mu and sales unit price, etc.), conduct nonlinear programming processing on the planting situation in the next 15 years (2024-2030), and obtain the optimal planting plan to maximize profits. And models are established in two situations when the output exceeds the expected sales volume, thereby ensuring the reality and rigor of the discussion.

2.1. Nonlinear programming

The general form of nonlinear programming problem can be expressed as:

$$\min_x f(x) \text{ or } \max_x f(x) \tag{1}$$

And meet the following constraints:

$$g_m(x) \le 0 \tag{2}$$

$$h_n(x) = 0 \tag{3}$$

Among them, x is the vector of the optimization variable; f(x)is the objective function, usually nonlinear; $g_m(x)$is an inequality constraint function; $h_n(x)$is the equality constraint function.

The objective function is the mathematical formula for calculating the maximum profit, and $g_m(x)$and $h_n(x)$ are the restrictive conditions for calculating the profit in this problem. Therefore, nonlinear programming can fit the formula for maximum profit well. Therefore, this article applies nonlinear programming models to solve for maximum profit and provide the optimal solution.

2.2. Modeling

This article needs to provide the optimal planting plan for crops from 2024 to 2030, which requires solving for the maximum total income of crop planting. Based on similar studies, our function model aims at maximizing economic benefits. We adopt the sales revenue of crops minus the main costs (in this paper, only the planting costs are considered) as the main indicators of economic balance and benefits, which is our objective function [2].

Below, we will analyze the two situations of using unsold waste treatment and reducing prices by 50% for parts that exceed expected sales volume:

2.2.1 Remaining goods were wasted

When the output exceeds the expected sales volume and there are excess unsold goods, resulting in waste, the objective function of total revenue is:

$$\max \sum_{t=2024}^{2030} \sum_{i=1}^{54} \sum_{j=1}^{41} \tag{4}$$

The actual calculation process of this formula is:

$$\min(x_{ij}^{t} \times \text{Acre Yield}_j\ , \text{Expected Price of Sales}_j) \times \text{Unit Price of Sales}_j - x_{ij}^{t} \times \text{Cost of Planting}_j$$

This model actually has the following limitations [3]:

Plot type constraint: Set different crop types and quantity constraints for different types of land parcels, such as flat land, terraced fields, and hillside land where only grains can be grown, irrigated land where rice can be grown, and greenhouses where edible fungi can be grown.

If the type of the plot is not suitable for growing a certain crop j, then:

$$x_{ij}^{t} = 0 \tag{5}$$

Planting area constraint: The planting area of each piece of land cannot exceed the actual area of the cultivated land, that is:

$$\sum_{j=1}^{41} x_{ij}^{t} \le Area\ of\ Plot_i \ \ (\forall i, \forall t) \tag{6}$$

Repetitive planting constraint: To prevent yield reduction, the same crop should not be planted on the same plot for two consecutive years, namely:

$$x_{ij}^{t} \times x_{ij}^{t-1} = 0 \ \ (\forall i, \forall j, \forall t) \tag{7}$$

Legume rotation constraint: Considering the beneficial effects of legumes on the growth of other crops, leguminous crops should be planted at least once within three years, namely:

$$\sum_{t=T}^{T+2} \sum_{j \in Legume} x_{ij}^{t} \ge \varepsilon \tag{8}$$

$$(\forall i, T = [2024, 2027], \varepsilon\ is\ a\ positive\ value)$$

In addition, it is necessary to consider the constraints of setting different areas for different types of plots, limiting the second season crops of irrigated land to only Chinese cabbage, white radish, and red radish, and restricting the use of edible fungi in ordinary greenhouses in the second season.

In this case, the maximum gain is 3.2×10^6 yuan.

2.2.2 Remaining portion will be sold at 50% of the 2023 sales price

When the output exceeds the expected sales volume, the excess portion will be sold at 50% of the 2023 sales price. At this point, the objective function for the total revenue is:

$$\max \sum_{t=2024}^{2030} \sum_{i=1}^{54} \sum_{j=1}^{41} \tag{9}$$

The actual calculation process of this formula is:

$$\min(x_{ij}^{t} \times \text{Acre Yield}_j\ , \text{Expected Price of Sales}_j) \times \text{Unit Price of Sales}_j$$
$$+ \max(0, x_{ij}^{t} \times \text{Acre Yield}_j - \text{Expected Price of Sales}_j) \times 0.5 \times \text{Unit Price of Sales}_j$$

$$-x_{ij}^{t} \times \text{Cost of Planting}_j$$

This time, the constraint conditions are similar to those in Section 2.2.1, that is, from (5) to (8). Our simulation results show that the profit can be maximized to 1.41×10^7 yuan.

3. Analysis of crops based on Monte Carlo optimization

Next, based on the constraints in the previous chapter section, we additionally considered the influence of uncertainties, that is, for specific crops (wheat and corn), we increased the volatility variables of expected sales volume, yield per unit, planting cost and selling price. And the method of sensitivity analysis was adopted to explore the influence of uncertain factors on the optimal planting plan.

3.1. Monte Carlo optimization

Monte Carlo optimization is a computational method that solves problems through random sampling and statistical simulation [4]. Its core principle is to establish a probability distribution model, conduct large-scale random experiments with the aid of computers, and achieve statistical convergence by using the law of large numbers [5].

3.1.1 Estimation and Expectations

In Monte Carlo optimization, the expected value of the objective function is often estimated by the sample mean. For example, for the objective function $f(x)$, if this article generates N samples $x_1, x_2, \cdots, x_N$ at x, the estimated value of the objective function at x is the average of these samples [6]:

$$f(x) = \frac{1}{N}\sum_{i=1}^{N} f(x_i) \tag{10}$$

3.1.2 Global optimization strategy

The key to Monte Carlo optimization lies in its global optimization ability, especially in cases where the solution space dimension is high or the complexity is large. It avoids getting stuck in local optima through random sampling, increasing the likelihood of finding the global optimal solution.

We need to choose an appropriate sampling strategy to ensure sufficient exploration of the solution space. Common strategies include uniform random sampling and importance sampling.

3.1.3 Variance and confidence intervals

To evaluate the accuracy of the estimation, Monte Carlo methods typically calculate the variance and confidence interval of the objective function estimation. The variance of the sample mean can be used to measure the stability of the estimation. By calculating the confidence interval, we can determine the probability of the objective function value falling within a certain range to reflect the reliability of the estimation.

3.1.4 Optimization process

The optimization process of Monte Carlo optimization usually includes the following steps:

Initialization: Generate initial solutions and sample points.

Evaluation: Calculate the objective function value of the sample points.

Update: Update the current optimal solution based on the evaluation results.

Iteration: Repeat the above steps and approach the global optimal solution through gradual optimization.

3.2. Sensitivity analysis[7]

Sensitivity Analysis is a method of studying the sensitivity of a model's output to changes in input variables. It can help understand the behavior of the model, evaluate the impact of uncertainty on decision-making, and optimize model parameters. The following are the basic mathematical principles and methods of sensitivity analysis:

The core of sensitivity analysis is to evaluate the response of model output y to changes in input variables. Suppose we have a model whose output y depends on n input variables. Then we study the sensitivity of the output to changes in the input near a specific input point through local sensitivity analysis. Commonly used local sensitivity indicators include partial derivatives and sensitivity coefficients.

Partial derivative: For the model output $y = f(x_1, x_2, \cdots, x_n)$, local sensitivity can be measured by calculating the partial derivative:

$$\text{Sensitivity}_{x_i} = \frac{\partial f}{\partial x_i} \tag{11}$$

This indicates the amount of change in output y when there is a slight change in input.

Sensitivity coefficient: Calculate the relative change of the model output to the input variable:

$$\text{Sensitivity}_{x_i} = \frac{\partial f / \partial x_i}{f} \tag{12}$$

To sum up, we evaluate the objective function through Monte Carlo optimization method, and achieves global optimization by analyzing uncertain factors. Sensitivity analysis can explore the degree to which uncertain factors affect the results, thereby further determining the maximum value of the objective function.

3.3. Modeling

3.3.1 Objective function

This part will still use the maximum profit value as the objective function, that is:

$$\max \sum_{t=2024}^{2030} \sum_{i=1}^{54} \sum_{j=1}^{41} \tag{13}$$

The actual calculation process of this formula is:

$$\min(x_{ij}^{t} \times \text{Acre Yield}_j\ , \text{Expected Price of Sales}_j) \times \text{Unit Price of Sales}_j - x_{ij}^{t} \times \text{Cost of Planting}_j$$

3.3.2 Constraints

Similarly, we still need to consider numerous constraints.

Land parcel type constraint, namely:

$$x_{ij}^{t} = 0 \tag{14}$$

Planting area constraint, namely:

$$\sum_{j=1}^{41} x_{ij}^{t} \le Area\ of\ Plot_i \ \ (\forall i, \forall t) \tag{15}$$

Repetitive planting constraints, namely:

$$x_{ij}^{t} \times x_{ij}^{t-1} = 0 \ \ (\forall i, \forall j, \forall t) \tag{16}$$

Legume rotation constraint, namely:

$$\sum_{t=T}^{T+2} \sum_{j \in Legume} x_{ij}^{t} \ge \varepsilon \tag{17}$$

$$(\forall i, T = [2024{,}2027], \varepsilon\ is\ a\ positive\ value)$$

3.3.3 Uncertainty factors

Expected sales volume: Based on experience, the annual growth rate of wheat and corn is 5% - 10%, while that of other crops is ±5%.

$$Quantity\ of\ Sale_j^t = Quantity\ of\ Sale_j^{2023} \times (1 + \gamma_{Quantity\ of\ Sale,j}^t) \quad (18)$$

Acre Yield: Due to climate factors, the growth rate of acre yield is ±10%.

$$Acre\ Yield_j^t = Acre\ Yield_j^{2023} \times (1 + \gamma_{Acre\ Yield,\mathrm{j}}^t) \quad (19)$$

Planting cost: Under the influence of market conditions, the average annual cost of crop cultivation increases by ±5%.

$$Cost\ of\ Planting_j^t = Cost\ of\ Planting_j^{2023} \times (1 + \gamma_{Cost\ of\ Planting,\mathrm{j}}^t) \quad (20)$$

Sales price: Due to market regulation, the sales price trends of different crops vary. For instance, the sales prices of grain crops remain stable, while those of vegetable crops increase by ±5% annually.

$$Price\ of\ Sales_j^t = Price\ of\ Sales_j^{2023} \times (1 + \gamma_{Price\ of\ Sales,\mathrm{j}}^t) \quad (21)$$

3.3.4 Simulation

Due to the many uncertain factors involved in determining the optimal planting plan in this article, sensitivity analysis is conducted to determine how to determine the optimal plan. The higher the sales volume and yield per mu of crops, the greater the profit; The higher the selling price of edible mushrooms, the greater the profit. At the same time, the annual change rate of crop planting costs is the same as that of vegetable sales prices and morel mushroom sales prices. Therefore, in order to obtain maximum profit, the sales volume and yield per mu of crops are taken as the maximum annual growth rate, and the sales price of edible mushrooms is taken as the minimum annual decrease rate, as shown in Table.1:

Table.1. Values of Uncertain Factors

Uncertain factors	Annual change rate
Crop sales volume	**5**%
Crop yield per mu	**10**%
Selling price of edible mushrooms	**−1**%

Therefore, while keeping the above variables constant, this article only discusses the impact of the annual growth rate of wheat and corn on the maximum profit value.

3.4.1 Simulation results

The impact of the annual growth rate of wheat and corn on the maximum profit value is shown in Table.2. At this time, the annual growth rate of wheat is 10%, and the annual growth rate of corn is 10%, with a maximum profit of 1.997×10^8yuan.

Table.2. The Impact of Annual Growth Rates of Wheat and Corn on the Maximum Profit Value

Annual growth rate of wheat (%)	Annual growth rate of corn (%)	Maximum profit value (yuan)
5	5	1.798×10^8
5	6	1.801×10^8
6	5	1.809×10^8
6	6	1.812×10^8
6	7	1.827×10^8
7	6	1.811×10^8
7	7	1.845×10^8
7	8	1.851×10^8
8	7	1.862×10^8
8	8	1.884×10^8
8	9	1.892×10^8
9	8	1.910×10^8
9	9	1.914×10^8
9	10	1.925×10^8
10	9	1.941×10^8
10	10	1.997×10^8

4. Research on Maximum Profit Based on Grey Relational Analysis Method

Finally, on the basis of the first two parts, consider new uncertainties (such as land type, planting area, etc.), as well as the correlation between sales volume and cost, output, etc. After conducting a correlation analysis, the factors with high correlation were given priority for analysis. Then, combined with the specific circumstances of cultivation and sales in 2023, nonlinear programming processing was carried out for the future planting situation to re-obtain the optimal planting plan.

This chapter not only employs model methods such as nonlinear programming, Monte Carlo optimization and sensitivity analysis, but also adopts the Pearson correlation coefficient to explore the correlation between sales volume and price cost.

4.1. Modeling

This part will still use the maximum profit value as the objective function, that is:

$$\max \sum_{t=2024}^{2030} \sum_{i=1}^{54} \sum_{j=1}^{41} \tag{22}$$

The actual calculation process of this formula is:

$$\min(\mathrm{x}_{\mathrm{ij}}^{\mathrm{t}} \times \text{Acre Yield}_{\mathrm{j}}\,, \text{Expected Price of Sales}_{\mathrm{j}}) \times \text{Unit Price of Sales}_{\mathrm{j}} - \mathrm{x}_{\mathrm{ij}}^{\mathrm{t}} \times \text{Cost of Planting}_{\mathrm{j}}$$

4.1.1 Constraints

Similarly, this article still needs to consider numerous constraints, such as

Land parcel type constraint, namely:

$$x_{ij}^{t} = 0 \tag{23}$$

Planting area constraint, namely:

$$\sum_{j=1}^{41} x_{ij}^{t} \le Area\ of\ Plot_i \ \ (\forall i, \forall t) \tag{24}$$

Repetitive planting constraints, namely:

$$x_{ij}^{t} \times x_{ij}^{t-1} = 0 \ \ (\forall i, \forall j, \forall t) \tag{25}$$

Legume rotation constraint, namely:

$$\sum_{t=T}^{T+2} \sum_{j \in Legume} x_{ij}^{t} \geq \varepsilon \tag{26}$$

$$(\forall i, T = [2024,2027], \varepsilon \; is \; a \; positive \; value)$$

4.1.2 Uncertain factors

Expected sales volume

$$Quantity\ of\ Sale_j^t = Quantity\ of\ Sale_j^{2023} \times (1 + \gamma_{Quantity\ of\ Sale,j}^t) \tag{27}$$

Acre Yield

$$Acre\ Yield_j^t = Acre\ Yield_j^{2023} \times (1 + \gamma_{Acre\ Yield,j}^t) \tag{28}$$

Planting cost

$$Cost\ of\ Planting_j^t = Cost\ of\ Planting_j^{2023} \times (1 + \gamma_{Cost\ of\ Planting,j}^t) \tag{29}$$

Selling price

$$Price\ of\ Sales_j^t = Price\ of\ Sales_j^{2023} \times (1 + \gamma_{Price\ of\ Sales,j}^t) \tag{30}$$

In addition to uncertain factors such as substitutability and complementarity between crops, this article also introduces uncertain factors such as the correlation between sales volume, price, and cost.

Generally, there is a certain correlation between the expected sales volume of crops, sales prices, and planting costs. According to economic principles, sales volume and selling price are mostly negatively correlated, meaning that an increase in price will lead to a decrease in demand, and vice versa. Meanwhile, due to market conditions, there is also a correlation between sales volume and planting costs. For example, an increase in costs may lead to a decrease in sales volume, while a decrease in costs may promote an increase in sales volume. Therefore, this article analyzes the correlation between sales volume, price, and cost.

The Pearson correlation coefficient, also known as the product difference correlation coefficient, is used to measure the degree of linear correlation between two variables [8]. The value of the correlation coefficient ranges from -1 to 1. Its calculation expression is:

$$r = \frac{\sum(X - \overline{X})(Y - \overline{Y})}{\sqrt{\sum(X - \overline{X})^2 \sum(Y - \overline{Y})^2}} \tag{31}$$

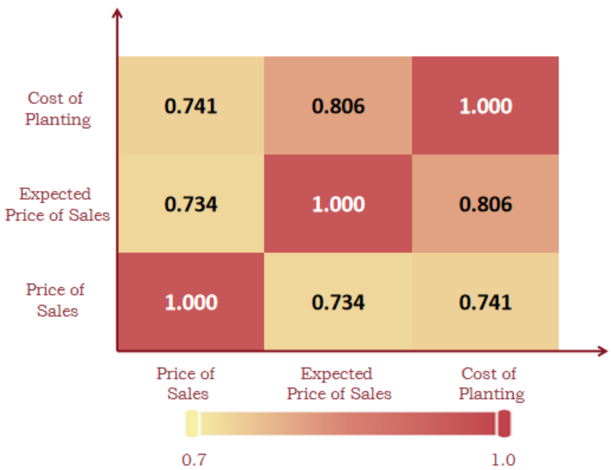

Figure 1. Correlation analysis between sales price, cost, and expected sales volume

By sorting out the calculated data, we can draw the heat map shown in Fig 1. Heat maps can visually represent the distribution of various types of data in a city through different colors and densities, improving the scientificity and efficiency of decision-making [9]. As shown in Fig 1, there is a significant positive correlation between the total sales price, total output, and total cost. Because the correlation coefficients between them are all above 0.6, it can be considered that there is a strong correlation [10]. As the total cost increases, the total selling price often also increases. Among them, the impact of cost on sales price is greater than the impact of expected sales volume on sales price, that is, the impact of cost on sales price is the greatest between the two.

4.2. Final results

In summary, when seeking the best planting plan, cost changes should be given priority, followed by changes in expected sales volume.

Therefore, the final planting optimization formula is

$$\max \sum_{t=2024}^{2030} \sum_{i=1}^{54} \sum_{j=1}^{41} \tag{32}$$

The actual calculation process of this formula is:

$$\min(0.95 \times x_{ij}^t \times \text{Acre Yield}_j, \text{Expected Price of Sales}_j) \times 0.99 \times \text{Unit Price of Sales}_j - 0.9 \times x_{ij}^t \times \text{Cost of Planting}_j \tag{33}$$

Similarly, keeping the above variables constant, we will only discuss the impact of the annual growth rate of wheat and corn on the maximum profit value here. As shown in Table Ⅲ, when the annual growth rate of wheat is 10% and the annual growth rate of corn is 10%, there is a maximum profit value of 2.126×10^8 yuan.

Table.3. The Impact of Annual Growth Rates of Wheat and Corn on the Maximum Profit Value

Annual growth rate of wheat (%)	Annual growth rate of corn (%)	Maximum profit value (yuan)
5	5	1.807×10^8
5	6	1.834×10^8
6	5	1.859×10^8
6	6	1.867×10^8
6	7	1.886×10^8
7	6	1.901×10^8
7	7	1.924×10^8
7	8	1.933×10^8
8	7	1.960×10^8
8	8	1.978×10^8
8	9	1.998×10^8
9	8	2.015×10^8
9	9	2.032×10^8
9	10	2.067×10^8
10	9	2.098×10^8
10	10	2.126×10^8

5. Conclusion

Through our previous analysis, we successfully established a nonlinear model for such problems, and based on the existing data, obtained the best planting plans under different situations, and also provided the corresponding maximum profits. During this process, we took into account the possible uncertain variables and disturbing factors in reality, striving to make our model and results more accurate and closer to the actual situation. Although the factors we considered are still limited, we have proved through data that we have provided a feasible solution for addressing such problems. Compared with the original nonlinear programming method, the planning method proposed in this paper, by solving in stages, not only avoids the trap of local optimal solutions but also ensures the attainment of the global optimal solution. By reasonably decomposing the problem and appropriately introducing uncertain variables, we have effectively simplified the constraint handling. Especially in the case of the influence of a single factor, the existence of constraints actually narrows the feasible domain range, thereby reducing the computational complexity. Although our method's application in real-world multi-constraint nonlinear programming problems still needs further research. However, by using the idea of gradually adding uncertain factors, this method has the potential to solve more complex problems. Future research can further explore its application in multi-constraint and multi-objective optimization.

In conclusion, our method demonstrates higher efficiency and stability when dealing with nonlinear programming problems. Particularly, it shows significant advantages in terms of local optimality and constraint handling. This method not only achieves a breakthrough in theory but also provides a novel solution for practical optimization problems, possessing significant practical application value.

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