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Rural Crop Planting Strategy Based on the Simulated Annealing Algorithm

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Abstract. Rural agricultural economies need tailored strategies and intensive cultivation for sustainable development. In China, with limited arable land and a push for agricultural modernization, choosing the right crop planting strategies is essential to meet people's needs and boost agricultural production and the economy.For Problem 1, we created an integer programming model aiming for stable annual economic returns, with average annual planting revenue as the objective function. Two scenarios were considered: excess crops wasted or sold at half price. Using the simulated annealing algorithm, we found that the average annual revenue is 7,882,002.50 yuan in the first scenario and 8,659,569.25 yuan in the second.For Problem 2, we built a robust optimization model to account for the dynamic nature of the agricultural market, including potential risks from rising costs, falling prices, and declining demand. The model focuses on worst-case scenarios to develop a resilient planting strategy, reducing risks from market volatility. It uses minimum annual planting revenue as the objective function and parameter uncertainty sets to create a plan less sensitive to disturbances and effective under most conditions.For Problem 3, we constructed evaluation indicators to explore the substitutability and complementarity between crops, as well as their sales, planting costs, and prices. A grey relational analysis model was used to assess crop similarity. Prioritizing crops with higher returns and stable prices, we selected 29 crops, including legumes, for a new planting strategy. Compared to the strategy from Problem 2, the new plan has fewer crop rotations, more stable economic returns, and easier field management.This paper summarizes and analyzes the established models, providing a comprehensive evaluation of their advantages and limitations.

Keywords: Optimization Model, Integer Programming, Simulated Annealing, Robust Optimization

1. Introduction

The village has six types of farmland, totaling 1,213 acres, each suitable for different crops. Flat dry land, terraces, and slopes can support one season of grain crops. Irrigated land allows one or two crop seasons, while ordinary greenhouses support one season of vegetables and one of edible fungi. Smart greenhouses can grow two vegetable seasons. Chinese cabbage, white radish, and red radish are limited to the second season on irrigated land or ordinary greenhouses. Edible fungi grow only in fall

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and winter in ordinary greenhouses. Crops cannot be planted consecutively on the same plot, and legumes must be planted at least once every three years. Planting areas should be well-managed and appropriately sized.

Problem 1: Determine the optimal crop planting strategy for 2024-2030 under two scenarios: ① excess crops beyond expected sales volume are wasted, and ② excess crops are sold at a 50% discount.

Problem 2: Considering fluctuating factors like a 5-10% growth in wheat and corn sales, ±5% fluctuation in other crops, ±10% yield variation due to climate, rising planting costs, and declining prices for edible fungi, provide the optimal crop strategy for 2024-2030.

Problem 3: Explore crop substitutive and complementary relationships and correlations between sales volume, prices, and planting costs using simulated data. Compare these results with those from Problem 2.

2. Problem analysis

2.1. Analysis of problem 1

With a maximum of two crops per plot per season, the planting scheme is represented using a 0-1 matrix, and the objective is to maximize the average annual farming revenue. Given the high dimensionality of the decision space, heuristic algorithms like simulated annealing are well-suited to solve the problem, ultimately determining the village's optimal planting strategy.

2.2. Analysis of problem 2

To address natural and market risks, it is necessary to maximize crop yields in the worst-case scenario, turning the problem into an uncertainty optimization. A robust optimization model is used, which is less sensitive to parameter fluctuations and is well-suited to obtain a resilient planting strategy under strict constraints.

2.3. Analysis of problem 3

Based on the price, yield, and cost of five types of crops, including grains, legumes, and vegetables, a grey relational model is used to select high cost-effectiveness crops and re-plan the planting scheme.

3. Basic assumptions

All farmland will be fully cultivated each season, with one crop per plot for dry land, terraces, slopes, and irrigated land, and up to two crops for greenhouses. Greenhouse crops are assumed to grow optimally, and grain yields will be based on 2023's highest figures. Sales volumes from 2024 to 2030 are estimated based on 2023, with all crops sold at the median price. Farmland is managed by plot, without considering plot size variations or maintenance costs, and parameter fluctuations are assumed to be statistically independent.

4. Model development and solution

4.1. Problem 1: development and solution of the optimization model

Based on the problem analysis and the given assumptions, integer programming should be used to solve the crop planting decision-making problem [1].

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4.1.1. Optimization model development

We define the optimization objective functions for two crop sales scenarios. For Scenario 1, any crops exceeding the expected sales volume will not be sold. In this case, the total revenue equals the normal sales revenue minus the planting costs. The normal sales volume is determined by the actual production of each crop in 2023, and the objective function is the average annual profit from planting and selling crops.

$$Income_{\text{average},1}$$

$$= \left[\sum_{k=2024}^{2030}\sum_{l=1}^{2} \begin{matrix} Prize_{i,j} \times Product_{i,j} \times x_{ij,k,l} \times min(LandArea_{i,j},\ PlantArea_{i,j,2023,l}) \\ -Cost_{\text{i,j}} \times PlantArea_{i,j,k,l} \times x_{ij,k,l} \end{matrix}\right]/8 \tag{1}$$

By summarizing the objective function and constraints, we obtain the optimization model corresponding to Scenario 1:

$$\max Income_{\text{average},1}$$

$$= \left[\sum_{k=2024}^{2030}\sum_{l=1}^{2} \begin{matrix} Prize_{i,j} \times Product_{i,j} \times x_{ij,k,l} \times min(LandArea_{i,j},\ PlantArea_{i,j,2023,l}) \\ -Cost_{\text{i,j}} \times PlantArea_{i,j,k,l} \times x_{ij,k,l} \end{matrix}\right]/8$$

s.t.

$$\sum_{\text{i}=1}^{41} x_{ij} = 1,\ x_{ij} = 0\ or\ 1\ ,$$

$$Left\_Boundary \leq X \leq Right\_Boundary\ ,$$

$$x_{ij,k,1} \times\ x_{ij,k,2} = 0,\ k \in \{2024, \ldots, 2030\} \tag{2}$$

$$x_{ij,m,1} +\ x_{ij,m,2} +\ x_{ij,m+1,1} +\ x_{ij,m+1,2} +\ x_{ij,m+2,1} + x_{ij,m+2,2} \geq 1,\ m \in \{2023, \ldots, 2028\},\ i \in \{1,2,3,4,5,17,18,19\}$$

$$\sum_{j=1}^{6} y_{ij,k,l} \leq 2,$$

in which,

$$y_{i1,k,l} =\ \sum_{j=1}^{6} x_{ij,k,l}\ ,\ \ y_{i2,k,l} =\ \sum_{j=7}^{20} x_{ij,k,l}\ ,$$

$$y_{i3,k,l} =\ \sum_{j=21}^{26} x_{ij,k,l}\ ,\ \ y_{i4,k,l} =\ \sum_{j=27}^{34} x_{ij,k,l}\ ,$$

$$y_{i5,k,l} =\ \sum_{j=35}^{66} x_{ij,k,l}\ ,\ \ y_{i6,k,l} =\ \sum_{j=67}^{74} x_{ij,k,l}\ ,$$

$$l = 1\ or\ 2,\ \ k \in \{2024, \ldots, 2030\}.$$

For Scenario 2, where the excess crops beyond the expected sales volume are sold at 50% of the original price, the total revenue for the year is calculated as: normal sales revenue + discounted sales revenue - total planting costs.

The objective function in this case should be formulated as follows:

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$$Income_{\text{average},2}$$

$$= \left[\sum_{k=2024}^{2030} \sum_{l=1}^{2} \begin{matrix} Prize_{i,j} \times Product_{i,j} \times min(LandArea_{i,j},\ PlantArea_{i,j,2023,l}) \times x_{ij,k,l} \\ +0.5 \times Prize_{i,j} \times Product_{i,j} \times max(LandArea_{i,j} - PlantArea_{i,j,2023,l}, 0) \\ \times x_{ij,k,l} - Cost_{\text{i,j}} \times PlantArea_{i,j,k,l} \times x_{ij,k,l} \end{matrix} \right] /8 \tag{3}$$

By summarizing the objective function and constraints, we obtain the optimization model corresponding to Scenario 2:

$$\max\ Income_{\text{average},2}$$

$$= \left[\sum_{k=2024}^{2030} \sum_{l=1}^{2} \begin{matrix} Prize_{i,j} \times Product_{i,j} \times min(LandArea_{i,j},\ PlantArea_{i,j,2023,l}) \times x_{ij,k,l} \\ +0.5 \times Prize_{i,j} \times Product_{i,j} \times max(LandArea_{i,j} - PlantArea_{i,j,2023,l}, 0) \\ \times x_{ij,k,l} - Cost_{\text{i,j}} \times PlantArea_{i,j,k,l} \times x_{ij,k,l} \end{matrix} \right] /8$$

s.t.

$$\sum_{\text{i}=1}^{41} x_{ij} = 1,\ x_{ij} = 0\ or\ 1\ ,$$

$$Left\_Boundary \leq X \leq Right\_Boundary\ ,$$

$$x_{ij,k,1} \times\ x_{ij,k,2} = 0,\ k \in \{2024, \ldots, 2030\}$$

$$x_{ij,m,1} +\ x_{ij,m,2} +\ x_{ij,m+1,1} +\ x_{ij,m+1,2} +\ x_{ij,m+2,1} + x_{ij,m+2,2} \geq 1,\ m \in \{2023, \ldots, 2028\},\ i \in \{1,2,3,4,5,17,18\} \tag{4}$$

$$\sum_{j=1}^{6} y_{ij,k,l} \leq 2\ ,$$

in which,

$$y_{i1,k,l} = \ \sum_{j=1}^{6} x_{ij,k,l}\ ,\ \ y_{i2,k,l} = \ \sum_{j=7}^{20} x_{ij,k,l}\ ,$$

$$y_{i3,k,l} = \ \sum_{j=21}^{26} x_{ij,k,l}\ ,\ \ y_{i4,k,l} = \ \sum_{j=27}^{34} x_{ij,k,l}\ ,$$

$$y_{i5,k,l} = \ \sum_{j=35}^{66} x_{ij,k,l}\ ,\ \ y_{i6,k,l} = \ \sum_{j=67}^{74} x_{ij,k,l}\ ,$$

$$l = 1\ or\ 2,\ \ k \in \{2024, \ldots, 2030\}.$$

Thus, we have obtained the optimization model needed to solve the planting strategy.

4.1.2. Model solution

After solving, the average annual revenue from crop planting is 7,882,002.50 yuan for Scenario 1, and 8,659,569.25 yuan for Scenario 2.

4.2. Problem 2: development and solution of the robust optimization model

Problem 2 involves the disturbance of multiple uncertain parameters, with their probability distributions being unclear, which increases the complexity and risk of optimization. To ensure stable returns, a robust optimization model is adopted to reduce the sensitivity of the planting strategy to

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uncertain parameters, ensuring stable income for the village under complex conditions. Based on assumption 7, we only consider relatively independent parameter fluctuations and establish a base uncertainty set to describe the range of these fluctuations.

$$U=\left\{\varphi:\ \sum\frac{|\varphi_i-\widehat{\varphi}_i|}{|\overline{\varphi_i}-\underline{\varphi_i}|}\leq\Gamma,\ |\varphi|\leq e\right\}\tag{5}$$

For a certain uncertain parameter within the set φ_i , $\overline{\varphi_i}$ 和 $\underline{\varphi_i}$ Representing the parameters separately φ_i the upper and lower bounds, $\widehat{\varphi}_i$ representing the predicted value of the uncertain parameter.

For the above linear optimization problem, the uncertain parameters representing planting risk can be evaluated by determining whether they have a positive correlation with the total net income from crops. This allows us to directly assess the values of uncertain parameters in the worst-case scenario [4].

4.3. Solving the optimization model

4.3.1. Problem 3: crop correlation analysis

The degree of correlation measures the relationship between factors in two systems. To explore crop substitutability, complementarity, and the links between sales volume, costs, and prices, we construct an index system and use a grey relational model. This index includes four indicators: selling price, yield per acre, planting cost per acre, and profit per acre (derived from price and yield). The grey relational model then analyzes the relationships between crops.

4.3.2. Crop correlation analysis

The number of crop types planted in the village for each major category is summarized in the table below:

Table 1: Summary of the number of crop types corresponding to each major crop category

Major Crop Categories	Number of Crop Types
Grains (Legumes)	5
Grains (Non-legumes)	11
Vegetables (Legumes)	3
Vegetables	18
Edible Fungi	4
Total	41

5. Conclusion

5.1. Advantages and disadvantages of the model

In the optimization model construction process, the optimal planting scheme was represented using a 0-1 matrix, considering multiple constraints to better meet the village’s crop production needs. A robust optimization model was employed to handle a large number of uncertain parameters, reducing sensitivity to parameter changes and ensuring stable agricultural income for the village. To address the substitutability and correlation between crops, a grey relational model was used to visually display the relationships between different crops and optimize the planting scheme accordingly. For the high-dimensional integer programming problem, the simulated annealing algorithm was applied, which is both easy to program and computationally efficient. However, as a pre-analysis method, robust optimization tends to yield conservative optimal solutions, potentially limiting higher agricultural profits. Additionally, the grey relational model involves subjective weighting, which may affect the accuracy of the analysis results.

5.2. Model outlook

A probability distribution can be assigned to parameter fluctuations, and a stochastic programming model can be used to develop a planting strategy that maximizes the village's potential for higher returns. By reviewing more literature, gathering factors that affect agricultural production and market prices, and conducting additional data experiments, more comprehensive and objective simulation results can be obtained.

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