Research on Multi-objective Optimization Model of the Planting Structure Based on TOPSIS

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Abstract. The problem of planting structure optimization is a multi-objective optimization decision problem. To solve this problem, this paper proposed a bi-level multi-objective optimization model of planting structure based on TOPSIS to optimize the agricultural planting structure. The optimal planting structure could be obtained by integrating the decision from both the upper-level and lower-level in the study area. The upper-level DM maximum total planting income with the minimum of total irrigation water could be obtained and the lower-level DMs maximum planting income with the minimum planting cost in sub-region. Finally, the constructed model was applied to optimize ternary planting structure of “food, cash and feed” in a part of the “Bohai Granary” of Science and Technology Demonstration Areas in Shandong Province in China. The optimal results of planting structure were obtained, and the comparison between the optimal results and the actual results was also made. It shows that the optimized planting structure has a better performance in terms of the increase in total planting income and the decrease in total irrigation water.

1. Introduction
In recent years, with the rapid population growth and economic development, many countries face the problem of unbalanced structure especially in those countries and regions that are constrained by resources and environment [1][2][4]. To date, a number of countries and regions around world have the capacity to produce food. However, in order to better achieve agricultural planting structure and modernize agricultural, feed crops must be separated from food crops. Importantly, the formation of the ternary planting structure of “food, cash and feed” is the only way to promote the development of agricultural economy [5][6].

The optimization of planting structure is obviously a multi-objective optimization problem. Which is based on the comprehensive consideration of factors such as land area, natural environment, irrigation conditions, market's requirement forecasting, crop rotation, as well as crop yields, quality and economic incomes [7]. Li Mo et al. (2014) [8]constructed a bi-level multi-objective optimization model of planting structure based fractional planning for agricultural irrigation problems, which was able to achieve maximum planting yield with minimum irrigation and integrated upper and lower management. Zhang Junling (2018) [9]developed a multi-objective optimization model to improve water use efficiency and to obtain the optimal crop planting scheme by combining the actual planting structure and planning in the current district. Zhang Fan et al. (2019) [10]obtained the relationship between crop acreage and market price through the Nerlove model, and handled the uncertainty expressed by the number of intervals and fuzzy numbers through the IFCBP model, which effectively addressed the concerns of two-level decision makers under uncertainty and helped regional managers to effectively plan future
resources. Li liuxing et al. (2020) [11]established a multi-objective optimization model for the scheduling of regional cluster planting structure based on the principle of "grain-based" and solved it by PSO algorithm to optimize the scheduling of regional cluster planting structure. Although the above methods provide some guidance for multi-objective optimization of planting structure. However, there is a lacuna in the research examining this topic in "food, cash and feed" ternary planting structure. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method transform the multi-level multi-objective problem into the multi-level bi-objective problem [12][13]. The introduction of TOPSIS method solves the problems of current planting structure optimization exactly. Therefore, this study presents a bi-level multi-objective optimization model of planting structure based on TOPSIS to allocating the proportion of “food, cash and feed” in the region and formulates a reasonable optimization scheme.

The main contribution of this paper is to establish a model. This model is a bi-level multi-objective optimization model of planting structure based on TOPSIS. Under this model, the TOPSIS method and fuzzy set theory are used to solve the model, and a reasonable "food, cash and feed" ternary planting structure is obtained. The model has the following advantages: 1) obtain the reasonable ternary planting structure of “food, cash and feed”; 2) obtain by integrating the decision from both the upper-level and lower-level; 3) deal with optimization problems in which each level has multi-objectives in the bi-level problem.

2. Research Process

2.1. Statement of the problem

While in recent years, food production has increased for many years, but there also have some problems such as periodic oversupply of food crop, imbalance between supply and demand of cash crops, shortage of feed crops[6]. The phenomenon of “food base hurt your dishes are hurt people in farming” is sometimes occurring. Therefore, promote the supply-side structure reform of agriculture and gradually shifting the dual structure of “food-cash” to the ternary structure of “food, cash and feed” is an effective measure to optimize the planting structure[5]. However, due to the very different types of regional factors in each area or region. The structure is hardly completing consistent, the way to determine the respective ternary planting structure is unclear and subjective. The pressing challenge is how to optimize the planting structure according to local conditions. Therefore, this paper proposes the bi-level multi-objectives optimization model of planting structure based on TOPSIS, the model consider the overall regional managers as well as managers of sub-region to improve the regional agricultural planting structure.

2.2. Multi-objective Optimization Model of the Planting Structure based on TOPSIS

The bi-level multi-objectives optimization model of planting structure based on TOPSIS is constructed. The upper-level DM (ULDM) maximum total planting income with the minimum of total irrigation water could be obtained and the lower-level DMs (LLDMs) maximum planting income with the minimum planting cost in sub-region[14][15][16][17]. The parameters in model are shown in Table1.

The model is as follows:

\[ \text{ULDM: maximize planting income and minimize irrigation water requirement} \]
\[ \max F_{11} = \sum_{m}^{M} (\sum_{i}^{I} a_{mi}A_{mi}X_{mi} + \sum_{j}^{J} b_{mj}B_{mj}Y_{mj} + \sum_{k}^{K} c_{mk}C_{mk}Z_{mk}) \]  
\[ \min F_{12} = \sum_{m}^{M} (\sum_{i}^{I} a_{mi}E_{mi} + \sum_{j}^{J} b_{mj}F_{mj} + \sum_{k}^{K} c_{mk}G_{mk}) \]  

\[ \text{LLDM: maximize planting income and minimize planting cost} \]
\[ \max F_{21m} = \sum_{i}^{I} a_{mi}A_{mi} + \sum_{j}^{J} b_{mj}B_{mj} + \sum_{k}^{K} c_{mk}C_{mk}, \forall m \]
\[ \begin{align*}
\min F_{22*} &= \sum_i^I a_{mi}O_{mi} + \sum_j^J b_{mj}P_{mj} + \sum_k^K c_{mk}Q_{mk}, \forall m \\
\text{Constraints of planting area:} & \\
\sum_m^M \left( \sum_i^I a_{mi} + \sum_j^J a_{mj} + \sum_k^K a_{mk} \right) &= T_{\text{max}} \\
R_{m_{\text{max}}} \leq \sum_i^I a_{mi} + \sum_j^J a_{mj} + \sum_k^K a_{mk} &\leq R_{m_{\text{max}}} \\
a_{ij} \leq a_{mi} \leq a_{ij}, b_{ij} \leq b_{mj}, c_{ij} \leq c_{mk} \leq c_{Uij} \\
\text{Constraints of food security:} & \\
\sum_m^M \sum_i^I a_{mi}A_{mi} &\geq D_{\text{min}} \\
\text{Constraints of irrigation water:} & \\
\sum_m^M \left( \sum_i^I a_{mi}E_{mi} + \sum_j^J a_{mj}F_{mj} + \sum_k^K a_{mk}G_{mk} \right) &\leq S_{\text{max}} \\
\text{Non-negativity constraints:} & \\
a_{mi} \geq 0, b_{mj} \geq 0, c_{mk} \geq 0 \\
\text{Where } F_{11}, F_{12}, F_{21*}, F_{22*} \text{ are objective functions, } m \text{ : area, } m = 1, 2, \ldots, M \\
\end{align*} \]

Table 1. Symbol definitions in the double-layer optimization model of planting structure based on TOPSIS.

| symbol | definition |
|--------|-------------|
| \(i\) | Types of food crops \(i = 1, 2, \ldots, I\) |
| \(j\) | Types of economic crops \(j = 1, 2, \ldots, J\) |
| \(k\) | Types of feed crops \(k = 1, 2, \ldots, K\) |
| \(a_{mi}\) | Planting area of \(i\)th grain crops in \(m\)th area |
| \(b_{mj}\) | Planting area of \(j\)th economic crops in \(m\)th area |
| \(c_{mk}\) | Planting area of \(k\)th feed crops in \(m\)th area |
| \(A_{mi}\) | The per unit yield of \(i\)th grain crops in \(m\)th area |
| \(B_{mj}\) | The per unit yield of \(j\)th economic crops in \(m\)th area |
| \(C_{mk}\) | The per unit yield of \(k\)th feed crops in \(m\)th area |
| \(X_{mi}\) | Unit price of \(i\)th grain crops in \(m\)th area |
| \(Y_{mj}\) | Unit price of \(j\)th economic crops in \(m\)th area |
| \(Z_{mk}\) | Unit price of \(k\)th feed crops in \(m\)th area |
| \(E_{mi}\) | Irrigation water consumption of \(i\)th grain crops in \(m\)th area |
| \(F_{mj}\) | Irrigation water consumption of \(j\)th economic crops in \(m\)th area |
| \(G_{mk}\) | Irrigation water consumption of \(k\)th feed crops in \(m\)th area |
| \(O_i\) | Production cost of \(i\)th grain crops |
| \(P_j\) | -Production cost of \(j\)th economic crops |
| \(Q_k\) | -Production cost of \(k\)th feed crops |
3. Model Application

3.1. Study Area

The model was applied to Dezhou city, Binzhou City and Dongying City, which are parts of the “Bohai Granary” Science and Technology Demonstration Zone in Shandong Province to optimize the ternary planting structure of "grain, economy and fodder". Aiming at the main crops in three cities, the optimization objects are grain crops: wheat and corn, economic crops: peanuts and cotton, feed crops: green fodder, etc. The optimized typical year is 2018.

3.2. Data Preparation

In order to optimize the planting structure in the "Bohai Granary" demonstration area in Shandong Province, such as Dezhou, Binzhou, and Dongying, the planting structure will be optimized. The main data refers to the “2019 China Statistical Yearbook”, "2019 Shandong Province Statistical Yearbook", China Brick agricultural big data terminal, agricultural product price information network, China agricultural big data network and the big data platform of Bohai Granary Science and Technology Demonstration Project. According to the irrigation quotas of major crops in Shandong Province, the total available irrigation water in Dezhou, Binzhou and Dongying is 24,001,000,020.00m³.

Table 2. Basic data 1 of the planting structure optimization model.

| REGION  | THE YIELD PER UNIT AREA(KG/HM²) | THE AVERAGE UNIT PRICE(YUAN/KG) |
|---------|---------------------------------|----------------------------------|
|         | wheat | corn | peanuts | cotton | green fodder | wheat | corn | peanuts | cotton | green fodder |
| DEZHOU  | 6621  | 7027 | 3951     | 1306   | 16206        | 2.52  | 1.96 | 7.40    | 15.60  | 20.10       |
| BINZHOU | 6141  | 6539 | 3458     | 986    | 15500        | 2.52  | 1.96 | 7.40    | 15.60  | 20.10       |
| DONGYIN | 5840  | 5972 | 2150     | 705    | 17002        | 2.52  | 1.96 | 7.40    | 15.60  | 20.10       |

Table 3. Basic data 2 of the planting structure optimization model.

| REGION  | GROSS IRRIGATION QUOTA(M³/HM²) | PLANTING COST(YUAN/HM²) |
|---------|---------------------------------|-------------------------|
|         | wheat | corn | peanuts | cotton | green fodder | wheat | corn | peanuts | cotton | green fodder |
| DEZHOU  | 15390 | 9015 | 11400   | 11340  | 10935        | 12469.2 | 12729 | 19962.3 | 38511.3 | 4515          |
| BINZHOU | 15390 | 9015 | 11400   | 11340  | 10935        | 12469.2 | 12729 | 19962.3 | 38511.3 | 4515          |
| DONGYIN | 15390 | 9015 | 11400   | 11340  | 10935        | 12469.2 | 12729 | 19962.3 | 38511.3 | 4515          |
Table 4. The maximum and minimum planting areas of each crop in three cities

| REGION | MINIMUM PLANTING AREA (HM²) | MAXIMUM PLANTING AREA (HM²) |
|--------|-----------------------------|-----------------------------|
|        | wheat | corn | peanuts | cotton | green fodder | wheat | corn | peanuts | cotton | green fodder |
| DEZHOU | 436360 | 417270 | 1702 | 458 | 654539 | 625904 | 2554 | 19088 | 686 |
| BINZHOU | 228094 | 253608 | 2562 | 632 | 342140 | 380412 | 3842 | 38353 | 948 |
| DONGYIN | 91054 | 85890 | 590 | 20806 | 126834 | 884 | 31208 | 1899 |

3.3. Model Solving Process

3.3.1. The TOPSIS for the upper-level optimization problem of planting structure

According to the relative importance of goals, it assumes that \( \lambda_1 = 0.5, \lambda_2 = 0.5, p = 2 \) in the equations \( d_{\text{PIS}}^p(x) \) and \( d_{\text{NIS}}^p(x) \). According to the model, the maximum satisfactory level of \( \alpha \) is 0.9916849, the satisfactory solution of upper-level problem is shown in table 5.

Table 5. The satisfactory solution of upper-level problem (hm²)

| Region   | wheat   | corn   | peanuts | cotton | green fodder |
|----------|---------|--------|---------|--------|--------------|
| Dezhou   | 460058.7 | 603256.3 | 2554.0 | 19088.0 | 686.0        |
| Binzhou  | 228094.0 | 366843.0 | 3842.0 | 38353.0 | 948.0        |
| Dongyin  | 97084.0  | 128834.0 | 884.0  | 20806.0 | 1899.0       |

The maximum total planting income in the upper-level is 29703857250 yuan, which is \( F_{11} = 9703857250 \), the minimum total irrigation water requirement in the upper-level is 2300622585 m³, which is \( F_{12} = 3000622585 \).

3.3.2. The TOPSIS for the bi-level optimization problem of planting structure

In the practical bi-level optimization problem of planting structure, the decision makers (DMs) take into account both upper-level and lower-level at the same time. According to the relative importance of goals, it assumes that \( \lambda_1 = \lambda_2 = 0.125, j = 1, 2, \ldots, 6, p = 2 \), of equations \( d_{\text{PIS}}^p(x) \) and \( d_{\text{NIS}}^p(x) \) when \( p = 2 \). According to the model, the maximum satisfactory level of \( \delta \) is 0.8070397, the satisfactory solution of bi-level problem is shown in table 6.

Table 6. The satisfactory solution of bi-level optimization model of planting structure (hm²)

| Region | wheat   | corn   | peanuts | cotton | green fodder |
|--------|---------|--------|---------|--------|--------------|
| Dezhou | 494568.8 | 568746.2 | 2554.0 | 19088.0 | 686.0        |
| Binzhou | 280469.6 | 314467.4 | 3842.0 | 38353.0 | 948.0        |
| Dongyin | 115353.4 | 105753.3 | 884.0  | 25617.3 | 1899.0       |

The maximum of the total planting income in the upper-level is 30079528650 yuan, which is \( F_{11} = 30079528650 \), the minimum of the total irrigation water requirement in the upper-level is 2395378472 m³, which is \( F_{12} = 2395378472 \). The maximum of the planting income in the lower-level of Dezhou city, Binzhou City and Dongying City with the objective values \( F_{211} = 16789499734 \) yuan, \( F_{212} = 9379005435 \) yuan, \( F_{221} = 3911023481 \) yuan respectively. The minimum of the planting cost in the
lower-level of Dezhou City, Binzhou City and Dongying City with the objective values \( F_{22} = 14076040557 \) yuan, \( F_{32} = 8837917434 \) yuan, \( F_{23} = 3802006181 \) yuan respectively.

### 4. Results Analysis

The results obtained were compared with actual results. The optimized results of this paper show that the total planting income increased by 135767630.10 yuan and the total irrigation water requirement decreased by 65721548.5 m\(^3\). The planting income of Dezhou City decreased by 79427729.3 yuan, and the planting income of Binzhou City and Dongying City increased by 84204255.04 yuan and 13099104.38 yuan respectively. The planting cost of Dezhou City, Binzhou City and Dongying City decreased by 22214640.80 yuan, 50829546.12 yuan and 7246961.65 yuan respectively. The specific results are shown in Table 7, Table 8, Table 9, Figure 1, Figure 2 and Figure 3.

#### Table 7. Comparison of the optimized scheme and the actual scheme in Dezhou City (hm\(^2\))

|          | wheat  | corn   | peanuts | cotton | green fodder |
|----------|--------|--------|---------|--------|--------------|
| Optimized| 510630.8 | 557156.8 | 2554.0  | 14615.5 | 686.0        |
| Actual   | 545449.0 | 521587.0 | 2128.0  | 15907.0 | 572.0        |

#### Table 8. Comparison of the optimized scheme and the actual scheme in Binzhou City (hm\(^2\))

|          | wheat  | corn   | peanuts | cotton | green fodder |
|----------|--------|--------|---------|--------|--------------|
| Optimized| 290496.0 | 305119.5 | 3842.0  | 37674.5 | 948.0        |
| Actual   | 285117.0 | 317010.0 | 3202.0  | 31961.0 | 790.0        |

#### Table 9. Comparison of the optimized scheme and the actual scheme in Dongying City (hm\(^2\))

|          | wheat  | corn   | peanuts | cotton | green fodder |
|----------|--------|--------|---------|--------|--------------|
| Optimized| 130722.6 | 90044.4 | 884.0   | 25957.0 | 1899.0       |
| Actual   | 113818.0 | 107362.0 | 737.0   | 26007.0 | 1583.0       |

![Figure 1. Comparison of the optimized results and the actual results of the planting income](image)
5. Conclusion
According to the multi-objective and multi-level characteristics of planting structure, this paper constructs a bi-level multi-objective optimization model of planting structure based on TOPSIS. At the same time, the decision makers (DMs) take into account both upper-level and lower-level for realizing the sustainable development of regional agriculture. The upper-level DM (ULDM) maximizes the total planting income and minimizes the total irrigation water requirement in the meantime. The lower-level DM (LLDM) maximizes the planting income and minimizes the planting cost in each sub-region. The model was applied to optimize ternary planting structure of “food, cash and feed” in a part of the “Bohai Granary” of Science and Technology Demonstration Areas in Shandong Province in China. The optimal results of planting structure were obtained, and the comparison between the optimal results and the actual results was also made. It shows that the optimized planting structure have a better performance in terms of the increase in total planting income and the decrease in total irrigation water. From the adjustment scheme of planting area of various crops, the results meet the requirement of ternary planting structure of "food, cash and feed" to stabilize of food crops, optimize cash crops and expand feed crops. The obtained results validate the feasibility of the Bi-level multi-optimization model of the planting structure based on TOPSIS to the optimization of planting structure.

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