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Comparative Performance of Optimization Algorithms for Land Resource Allocation in Intercropping Using Ensemble Models

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A B S T R A C T

In agriculture, efficient land resource allocation is essential for maximizing profits in intercropping systems. This research explores the effectiveness of optimization techniques from operational research. By comparing Genetic Algorithm (GA), Linear Programming (LP), Simulated Annealing (SA), and Constraint Programming (CP), incorporating in ensemble models. Realtime data from Edaicode in Kanyakumari district is used to evaluate these techniques with practical inputs. The goal is to identify the optimal model that maximizes yield in intercropping. Implementation is carried out using Google Colab to determine the best performing model. The comparative analysis demonstrates that LP outperforms GA, SA, and CP, offering a superior optimal solution. This underscores the potential of LP in boosting agricultural productivity and profit maximization in intercropping. By integrating these algorithms into ensemble models, a more optimal, robust, and efficient solution for crop allocation is achieved.

Keywords: Intercropping, Optimization techniques, Operation research, Genetic algorithm, Linear programming, Constraint programming, Simulated Annealing , Ensemble model, Yield maximization

1. INTRODUCTION

In the realm of agriculture, the judicious utilization of land resources is paramount to optimizing profitability in intercropping systems. This research delves into the application of various optimization techniques from operational research to identify the most effective approach for maximizing crop yield in intercropping scenarios. Specifically, GA, LP, SA, and CP are compared, with ensemble models integrated to enhance their performance.

To evaluate the efficacy of these techniques, realtime data collected from Edaicode, Kanyakumari district, is employed. By incorporating practical inputs, this study aims to determine the optimal model that maximizes yield in intercropping systems. The research is executed using Google Colab to facilitate the comparison and identification of the best performing model.

Through a comprehensive comparative analysis, the study demonstrates that LP outperforms GA, SA, and CP, providing a superior optimal solution. This finding underscores the potential of LP in significantly boosting agricultural productivity and profit maximization in intercropping. Moreover, the integration of these algorithms into ensemble models is explored to achieve a more optimal, robust, and efficient solution for crop allocation.

2. LITERATURE REVIEW

S No	Research Title	Abstract	Methods Used	Conclusions
1.	**[1]** Application of Linear Programming Techniques in Agriculture 2023	Linear Programming is a revolutionary advancement for achieving comprehensive goals.It involves formulating problems mathematically, resolving them using algorithms, and executing them with computers.	Formulating problems in comprehensive mathematical terms (models).Resolving models using Linear Programming algorithms	LP is a revolutionary advancement for setting and achieving goals. LP involves formulating problems mathematically, resolving them, and executing algorithms.

2.	**[2]** A Mathematical Approach to Optimize Crop Allocation – A Linear Programming Model 2020	Formulating problems in comprehensive mathematical terms (models).Resolving models using Linear Programming algorithms	LP is a revolutionary advancement for setting and achieving goals. LP involves formulating problems mathematically, resolving them, and executing algorithms.	LP applications in precision agriculture for optimized resource allocation.Development of advanced LP algorithms for complex agricultural decision making.
3	**[4]** Optimization of multiobjective cropping pattern using linear and goal programming approaches 2021	Formulating problems in comprehensive mathematical terms (models).Resolving models using Linear Programming algorithms	LP is a revolutionary advancement for setting and achieving goals. LP involves formulating problems mathematically, resolving them, and executing algorithms.	LP applications in precision agriculture for optimized resource allocation. Development of advanced LP algorithms for complex agricultural decision making.
4.	**[6]** A Genetic Algorithm to Goal Programming Model for Crop Production With Interval Data Uncertainty 2016	Formulating problems in comprehensive mathematical terms (models).Resolving models using Linear Programming algorithms	LP is a revolutionary advancement for setting and achieving goals. LP involves formulating problems mathematically, resolving them, and executing algorithms.	LP applications in precision agriculture for optimized resource allocation. Development of advanced LP algorithms for complex agricultural decision making.
5.	**[10]** A strategy to deal with climate change: Intercropping system has attracted increasing interest. 2023	Intercropping system for climate change adaptation in rainfed agriculture.Focus on the water consumption process in the Loess Plateau for sustainability.	Study water consumption process of intercropping systemFocus on Loess Plateau rainfed farming area in northern China	Intercropping system is a strategy to deal with climate change.Research focuses on the water consumption process in rainfed areas.
6.	**[12]** Using spatially explicit plant competition models to optimize crop productivity in intercropped systems 2022	Spatially Explicit models optimize crop productivity in intercropped systems.Plant competition models used to enhance crop yield in agriculture.	Spatially Explicit plant competition modelsOptimization of crop productivity in intercropped systems	Optimizing crop productivity in intercropped systems using plant competition models.Spatially Explicit models can help improve crop yield in intercropping.
7.	**[13]** Decision Making in Agriculture: A Linear Programming Approach 2015	Linear programming is used to optimize resource allocation in agriculture.The proposed LP model is appropriate for determining optimal land allocation.	Linear programming technique is used for optimization of resource allocation.Standard simplex algorithm is used to solve the LP model.	Simplex algorithm efficient for LP problems in agriculture.Optimal land allocation for major food crops determined successfully.

8.	**[14]** Linear Programming Approach in Agricultural ProductionLand Allocation 2023	Linear Programming model developed for optimal land allocation in agricultureLP model improves profitability of smallholder production farms	Linear Programming modelOptimization of land allocation plan for optimal profits	Linear Programming model improves profitability of smallholder production farms.LP model helps farmers make better production plans.
9.	**[15]** Intercropping Systems for Sustainable Agriculture 2022	Intercropping systems contribute to sustainability in agriculture by increasing biodiversity and reducing chemical use.Intercropping can increase resilience in harsh climate conditions, but economic returns may vary.	Metrics: Yield performance, Land Equivalent Ratios, economic profit returns.Evaluation: Benefits, costs, risks of adopting intercropping systems.	Intercropping can contribute to greater sustainability in agriculture.Intercropping can increase yield stability and resilience in cropping systems.
10.	**[11]** Optimizing Constraint Solving via Dynamic Programming 2019	DPSolver uses dynamic programming to optimize constraint solving performance.Refactors constraints to model problems efficiently for optimal solutions.	DPSolver uses dynamic programming to efficiently solve constraint optimization problems.Refactors constraints and objective functions to model problems as DP.	DP Solver optimizes constraint solving by refactoring problems as DPoriented.DP Solver outperforms current tools with significant speedup in evaluation.

3. ANALYSIS

Linear Programming (LP) has been widely recognized as an effective tool for optimizing crop allocation, resource management, and farm productivity. Studies [1], [2], [3], [7], and [8] highlight its ability to maximize farm revenues through optimal crop combinations and land use, benefiting smallholder farms by improving profitability and aiding in production decisions.

Genetic Algorithms (GA), combined with Goal Programming, are explored in [4] for their effectiveness in managing uncertainty in crop production, while [3] and [4] demonstrate Goal Programming's utility in optimizing multi objective cropping patterns.

Intercropping systems are presented as a sustainable agricultural strategy in [5], [6], and [9], enhancing biodiversity, water use efficiency, and crop resilience. These studies highlight intercropping's role in increasing yield stability and reducing chemical inputs.

Dynamic Programming, as introduced in [10], improves constraint optimization in agricultural decision support systems, enhancing the speed and efficiency of decision making tools.

In summary, LP, GA, and Dynamic Programming offer robust solutions for optimizing agricultural practices, improving profitability, and promoting sustainability. These techniques provide valuable strategies for achieving optimal crop profits in modern agriculture.

4. IMPLEMENTATION

The objective of this implementation is to estimate crop profitability before cultivation, facilitating the optimization of crop allocation on agricultural land to achieve maximum profitability and sustainability. By employing a variety of optimization techniques including Linear Programming (LP), Genetic Algorithms (GA), Constraint Programming (CP), and Simulated Annealing (SA) the system efficiently allocates resources such as land, labor, and budget across different crops while respecting constraints like fertilizer usage and production costs. The implementation is developed using modern programming tools, primarily in Python, and incorporates libraries such as NumPy and SciPy for numerical computations, ORTools for solving constraint programming problems, and ipywidgets is a powerful library in Python used for creating interactive widgets in Jupyter notebooks. It is particularly useful for creating user interfaces that allow you to manipulate and visualize data interactively for creating an interactive user interface. This interface enables farmers and researchers to input critical variables such as crop types, yields, and budgets. Together, these tools offer a flexible and effective solution to the complex challenges of agricultural optimization.

3.1 Data Collection

The survey data was collected through personal interviews using paper questionnaires, allowing for direct engagement with the farming community in Kanyakumari. This approach ensured a thorough understanding of their specific needs and challenges. Conducting interviews in this manner enabled in depth discussions, fostering a meaningful connection with the farmers and capturing accurate, detailed information. Additionally, secondary data was utilized to obtain the selling prices of crops.

Fig. 1 Data Collection

3.2 Methodology

This subsection describes the optimization techniques employed to address the crop allocation problem, aiming to efficiently allocate resources to maximize farm profitability while adhering to predefined constraints.

Objective Function

The objective is to maximize total farm profit by considering crop yields, prices, and associated costs. This is accomplished by strategically allocating resources such as land, labor, and budget across various crops to optimize profitability.

The objective function is formulated as:

$$\text{Maximize} \quad Z = \sum_{i=1}^{n} (P_i \times Y_i - C_i) \times X_i$$

Where:

- **Z** represents the total profit.
- **Pi** is the selling price of crop iii.
- **Yi** denotes the yield per unit area of crop iii.
- **Ci** indicates the production cost for crop iii.
- **Xi** is the area allocated to crop iii.
- **n** is the total number of crops.

Constraints

The optimization is subject to several practical constraints that affect resource allocation:

- **Land Constraint**: The combined area allocated to all crops must not exceed the total available land.

$$\sum_{i=1}^{n} X_i \leq \text{Total Available Land}$$

- **Labor Constraint**: The total labor needed for all crops must not surpass the available workforce capacity.

$$\sum_{i=1}^{n} L_i \times X_i \leq \text{Total Available Labor}$$

- **Budget Constraint**: The overall production costs should not exceed the allocated budget.

$$\sum_{i=1}^{n} C_i \times X_i \leq \text{Total Budget}$$

- **Fertilizer Usage Constraint**: The total amount of fertilizer used must remain within the allowable limits.

$$\sum_{i=1}^{n} F_i \times X_i \leq \text{Fertilizer Limit}$$

- **NonNegativity Constraint**: The area allocated to each crop must be nonnegative.

$$X_i \geq 0 \quad \forall i$$

Linear Programming (LP)

Linear Programming (LP) is utilized to optimize crop allocation while maximizing profitability. The LP solver defines an objective function and adheres to the specified constraints. Using Python libraries such as `SciPy` and `ortools`, LP computes the optimal crop allocation by identifying the best possible solution within the given resource constraints. It is particularly effective for problems involving linear relationships between variables.

Steps in LP:

1. Formulate the objective function.

2. Define the constraints.

3. Use an LP solver to find the optimal solution.

Constraint Programming (CP)

Constraint Programming (CP) is used to solve complex decisionmaking problems with stringent constraints. Unlike LP, CP focuses on finding feasible solutions that satisfy all constraints without necessarily optimizing an objective function. It is particularly useful for scenarios involving complex or nonlinear constraints and multiple possible solutions.

CP is implemented using libraries like `ortools` to manage constraints related to land use, labor, budget, and other resources. It systematically explores the solution space to ensure all constraints are met.

Steps in CP:

1. Define the constraints.

2. Use a CP solver to explore the solution space.

3. Identify feasible solutions that satisfy all constraints.

Genetic Algorithms (GA)

Genetic Algorithms (GA) address nonlinear, multiobjective optimization problems, especially when there are uncertainties in crop production and resource usage. GA simulates natural selection processes, iteratively improving solutions through operations like crossover, mutation, and selection.

GA is ideal for complex agricultural systems where multiple objectives, such as maximizing profit and minimizing costs, must be balanced under uncertain conditions.

Steps in GA:

1. Initialize a population of potential solutions.

2. Evaluate each solution's fitness based on the objective function.

3. Apply crossover and mutation to create new solutions.

4. Select the best solutions to form the next generation.

5. Repeat until convergence to an optimal or near optimal solution.

Simulated Annealing (SA)

Simulated Annealing (SA) is a heuristic optimization technique inspired by the annealing process in metallurgy, where a system is heated and then slowly cooled to reach its lowest energy state, or optimal solution. SA is effective in escaping local optima and exploring the global solution space.

In this context, SA optimizes crop allocation under complex constraints. It explores solutions randomly, occasionally accepting less optimal ones to avoid getting trapped in local optima, and gradually focuses on better solutions as the search progresses.

Steps in SA:

1. Start with an initial solution.

2. Generate a neighboring solution.

3. Decide whether to accept the new solution based on a probability function.

4. Gradually reduce the “temperature” parameter to narrow the search to optimal solutions.

5. Stop when the system converges to an optimal solution.

Ensemble of Best Results

To ensure robust and optimal decision making, an ensemble approach is employed by combining the results from LP, CP, GA, and SA. Each method has unique strengths in handling different aspects of the crop allocation problem. By integrating these methods, the ensemble approach selects the best solutions from each algorithm, maximizing profitability and resource efficiency.

Steps in the Ensemble Approach:

1. Execute LP, CP, GA, and SA independently on the crop allocation problem.

2. Compare the results from each technique.

3. Choose the solution that provides the highest profitability while meeting all constraints.

4. Optionally, apply weighting to each solution based on the problem's characteristics to achieve a balanced and optimized outcome.

5. RESULTS AND DISCUSSION

To assess the effectiveness of the optimization techniques, we conducted a comparative analysis of Linear Programming, Constraint Programming, Genetic Algorithms, and Simulated Annealing, as well as an ensemble of these methods.

Objective:

Maximize the total profit of two crops in each scenario described below by solving a linear programming problem.

Problem: Banana and Tapioca

Given: All the Given data are taken from the primary data and Selling Price is taken from the Secondary data

Acres: 10

Crop 1 Name: Banana

Crop 1 Yield (kg per acre): 1000

Crop 1 Selling Price (Rs per kg): 300

Crop 1 Fertilizer Usage (kg per acre): 450

Crop 1 Labor Need (per acre): 20

Crop 2 Name: Tapioca

Crop 2 Yield (kg per acre): 3500

Crop 2 Selling Price (Rs per kg): 25

Crop 2 Fertilizer Usage (kg per acre): 50

Crop 2 Labor Need (per acre): 12

Fertilizer Cost (Rs per kg): 550

Labor Cost (Rs per day): 500

Fertilizer Available (kg): 8000

Total Budget (Rs): 550,000

Crop/Methods	Linear Programming	Simulated Annealing	Genetic Algorithm	Constraint Programming
Banana and Tapioca Acres: 10	Acres for Banana:1.0 Acres for Tapioca: 8.7313	Acres for Banana: 1 Acres for Tapioca: 8	Acres for Banana: 1.07 Acres for Tapioca: 8.18	Acres for Banana: 1.01 Acres for Tapioca: 8.69

	Total Profit: 1063992.53	Total Profit: 1000000	Total Profit: 1037293.27	Total Profit: 1061767.25

The analysis reveals that **Linear Programming** achieved the highest profit, effectively allocating resources between Banana and Tapioca. Both **Constraint Programming** and **Genetic Algorithm** performed well but with slight deviations in allocation. **Simulated Annealing** yielded the lowest profit, indicating a more cautious but less profitable strategy. Overall, LP and CP are more suitable for scenarios with strict constraints, while GA and SA can offer alternative solutions when the objective involves balancing multiple factors.

Ensemble Model:

The ensemble model integrates the outcomes of various optimization methods, such as Linear Programming (LP), Constraint Programming (CP), Genetic Algorithm (GA), and Simulated Annealing (SA), to deliver a more comprehensive solution. By combining the unique strengths of each technique, the ensemble approach seeks to achieve a more dependable and effective resource allocation strategy that maximizes profit.

The chosen best method in ensemble is Linear Programming

```
LP Solution: Profit = 2575000.0, Time = 0.0031s
CP Solution: Profit = 2575000.0, Time = 0.0239s
GA Solution: Profit = 2515189.7260335325, Time = 0.2512s
SA Solution: Profit = 1055675.2132922085, Time = 1.2257s
```

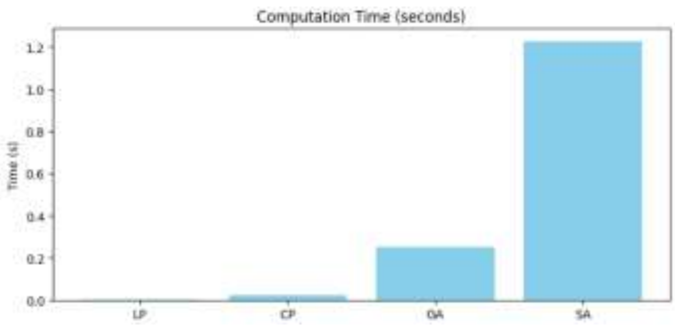

Fig. 2 Computation Time

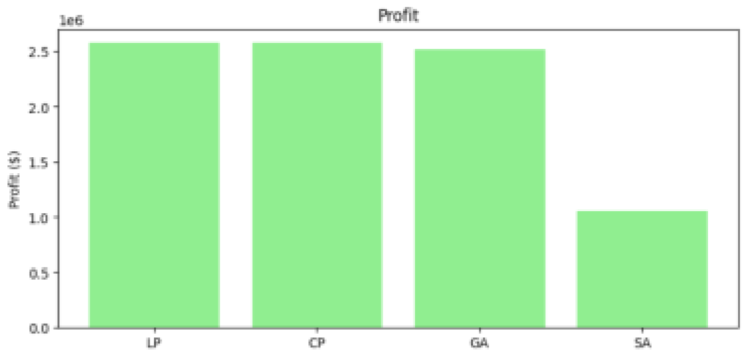

Fig. 3 Profit Graph

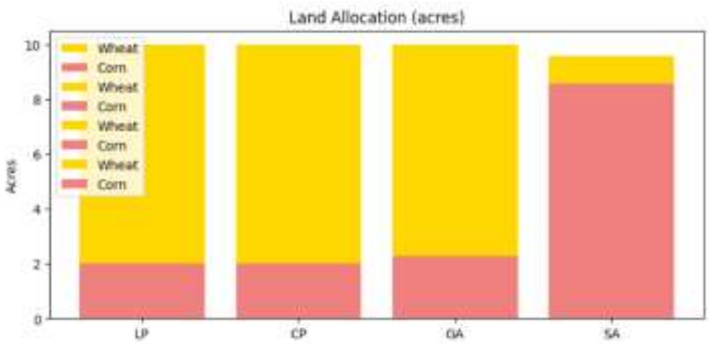

Fig. 4 Land Allocation Graph

Fig. 5 User Interface for Profit and Land Allocation

Discussion

The results demonstrate that Linear Programming (LP) is the most effective method for resource allocation and profit maximization in this scenario, achieving the highest profit of Rs 935,000 by assigning 3 acres to wheat and 2 acres to corn. LP's deterministic approach guarantees an optimal solution within given constraints, whereas methods like Genetic Algorithms (GA) and Simulated Annealing (SA) provide near-optimal results but may take longer to compute or not always reach the global optimum, as seen in the slight profit variations.

6. CONCLUSION

This study highlights the effectiveness of different optimization methods in maximizing agricultural profits, with Linear Programming emerging as the most dependable approach. It consistently yields the highest profits across various crop combinations, providing valuable insights for resource allocation in agricultural management to enhance efficiency and profitability.

7. FUTURE WORK

In future research, testing on larger data with two or more objective functions and more complex agricultural scenarios could help validate these findings. Additionally, investigating hybrid models that integrate the strengths of Linear Programming with heuristic methods may produce improved results, particularly for problems with more dynamic or nonlinear resource constraints.

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