

Optimized Placement of Aeroponic Towers using Various Machine Learning Algorithms

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I. INTRODUCTION

Abstract— The necessity to have sustainable efficient use of agriculture has raised the demand of the intelligent systems that justify the contemporary practices like aeroponics. The paper suggests Aeroponic Farm Optimization System based on AI, which is a combination of crop suitability prediction and the space allocation optimization, it is aimed at optimizing the use of limited space on the farm. Multi-layer perceptron ANN is applied in the assessment of the environmental conditions within the farm and subsequently assists in the determination of the crop suitability. The model takes into account some of the important parameters such as the type of crop, temperature, humidity, time taken by the sun, the pH of water, the air quality index, and the speed of the wind. In the light of these inputs, the system forecasts whether or not the chosen crop can be developed in the environment it is placed. After the checking of suitability, a hybrid spatial optimization module is used to identify the most optimal location of the aeroponic towers within the farm. It uses a hybrid approach of hexagonal lattice-based geometric packing and metaheuristic optimization techniques like Genetic Algorithm(GA) and Simulated Annealing(SA) to optimize even high tower density and meet the constraint of spacing and boundary. FastAPI and React with Vite were used to create the prototype, involving the use of Fast API as the backend services and React as the user interaction(frontend). It has been experimentally demonstrated that the hybrid optimization strategy has greater tower density than the standalone geometric methods and also has a strict constraint satisfaction. It provides a scalable and smart and efficient solution to aeroponic farm planning, a part of the intelligent agriculture and sustainable food production systems.

Keywords—Aeroponics, Artificial Neural Network, Genetic Algorithm, Simulated Annealing, Smart Agriculture, Optimization.

Agriculture is a significant phenomenon of the human civilization that feeds the people of the world, brings jobs and income to their lives. But even the old farming methods are currently facing a chain of significant challenges. Overpopulation has minimized the amount of arable land and the availability of freshwater is dwindling. In addition, unpredictable weather patterns have been brought about by climate change and hence complicate crop production. Conversely, the increase in the world population has led to the production of crops. This has motivated scientists and agriculturalists to find other agricultural methods in which they will yield more with less input. Therefore, the controlled environment agriculture, as well as the vertical farming practices, is gaining relevance in sustainable crop production [1], [2].

To counter the drawbacks of traditional soil-based methods of soil cultivation, a number of soilless farming methods have been devised to enhance the effectiveness of the utilization of resources and growth of plants. These methods are hydroponics, aquaponics and aeroponics. Water is applied in these methods as a nutrient media in order to enhance crop growth using little water. Fish farming has been employed in aquaponics as a source of nutrient to enhance plant growth as the roots of the plant enhance the quality of water. These methods enhance the efficiency with which the resources are utilized and at the same time keep the environmental aspects at par to enhance plant growth [3], [4].

Among these contemporary practices, the concept of aeroponics is regarded as among the most developed and productive types of soilless culture. In this technique the roots of the plants are suspended in the atmosphere and are occasionally sprayed with a well-granted solution. This will also be able to keep the roots well oxygenated and as well as to absorb nutrients effectively hence healthy growth of the plants. In addition, aeroponic towers can also be used to encourage vertical farming particularly in the urban cities where space is limited. In addition, this system also removes the chances of disease due to the absence of soil [5], [6]. The other notable benefit that can be reaped out of aeroponic farming is that it leads to the application of sustainable farming. Such kind of farming is normally water efficient and lowly demanding chemicals utilization. Moreover, it makes the most out of the space that is available. In the case that such a system is combined with the newest technology like

sensors, IoT, and AI, the environmental conditions may be observed in real-time. Earlier works have demonstrated that the application of machine learning and IoT-based monitoring can enhance the management of the environment to a significant level [7], [8].

However, as much as these benefits may be present, the efficiency of aeroponic farming is influenced by the spatial layout of aeroponic towers in the growing area. This can comprise the distance between the towers of aeroponic, air flow, amount of sunlight, and temperature difference. Poor location of the aeroponic towers can lead to inequalities of the environment which can impact the yield of the crops grown. Even as machine learning techniques have widely been applied in crop and environmental condition prediction, little focus has been on ideal siting of the aeroponic towers in the agricultural area [9], [10]. Therefore, the objective and aim of the project is to develop an intelligent system that has the capacity to offer the optimized recommendations on the location of the aeroponic towers based on the various machine learning technology. In this respect, the smart system will be capable of offering valuable advice depending on environmental conditions like temperature, humidity, sunlight, air quality, wind among other conditions. In this regard, the efficiency of the towers will be enhanced hence establishing a sustainable atmosphere of developing aeroponic farming.

II. LITERATURE SURVEY

There has been a lot of interest in aeroponics and vertical farming as a way of conducting more environmentally friendly methods of farming as opposed to the traditional methods of farming. With the ever increasing challenges in farming that are characterized by lack of enough land, inadequate water and unfavourable weather conditions, new farming methods are being invented to help in ensuring that there is a great yield at the same time resources are used efficiently. Controlled environment agriculture is the growth of crops under a controlled environment whereby temperature, humidity and light are controlled to provide the best environment in which the crops are likely to grow. This has resulted in the integration of modern technology in the methods of indoor farming.

Over the past few years, there have been a number of studies that have centred on the issue of introducing technologies like the Internet of Things (IoT), machine learning, and deep learning into the smart farming setting. Monitoring systems based on IoT allow constant control of environmental parameters and prevent the need to ensure an appropriate environment in terms of plant growth due to the existence of automated control systems. The same case applies to the study of plant growth patterns and prediction of crop performance, which now can be done with a higher degree of accuracy due to the implications of data-driven techniques. These strategies have been proved to have great potential in enhancing productivity, saving on resources and sustainable agriculture.

The more general uses of artificial intelligence and automation in vertical farming systems have been studied by researchers as well. The smart technologies would be able to help in monitoring the environment, crop management, and decision-making in controlled agricultural settings. Moreover, some works have given detailed knowledge on vertical farming technologies and raised some significant issues, including the use of energy, maintenance of the systems, and environmental control. In these studies, the authors stress on the need to implement high-tech technologies to enhance the overall functioning and sustainability of contemporary agricultural frameworks.

Other studies have focused on aspect of enhancing environmental management and system engineering in aeroponic farming. Different solutions have been suggested to track the health of plants, forecast crop conditions, and improve water and nutrient management in closed systems. The design and functionality of aeroponic towers such as water efficiency, structure and automation technologies have also been studied by engineering studies. The contributions have assisted in enhancing the reliability and efficiency of the systems used in indoor farming.

Even though much has been done in enhancing environmental monitoring, crop prediction, and automation, there still remains minimal focus on the spatial layout of aeroponic towers in the farming model. The positioning of towers may affect the distribution of air, sunlight and environmental harmony, which in turn directly affect the growth and productivity of plants. Majority of the available studies are on monitoring and predictive models and not on the actual layout planning. Thus, an increasing necessity in aeroponic farming systems in the enhancement of productivity and the use of resources is the provision of smart systems capable of analysing environmental factors along with spatial constraints and give optimal advice on where to place towers.

III. PROBLEM STATEMENTS

Aeroponics is a new farming method that allows plants to be free of soil and consume very little water and space as compared to the conventional farming method. In vertical farming, aeroponic towers are normally applied to ensure that areas are fully used to assist in effective crop production. The general performance of these systems however relies heavily on the position of the towers in the growing land. The sunlight exposure, temperature, humidity and airflow are some of the environmental factors that affect the growth of plants, and yield of crops. Moreover, space parameters such as the distance between towers, their layout, and the area available to practice cultivation also influence the system productivity and efficiency. In most existing configurations place locations are usually decided by the manual observation and trial-and-error techniques, this can be time consuming and is not necessarily going to achieve the best outcomes. Poor location may cause unequal distribution of sunlight, inadequate circulation, ineffective space utilization and eventual low crop yields. Thus, there is an increasing demand of an evidence based and smart mechanism that will be able to compare the environmental and spatial state to define the most appropriate location of towers. To overcome this obstacle, this project suggests a model of deep learning to predict and suggest the best location of aeroponic towers to enhance productivity, resource-effectiveness, and sustainability in the controlled farms.

The objectives of the proposed work as follows:

- To examine the environmental variables such as sunlight, temperature, humidity and airflow on the functionality of aeroponic towers.
- Developing and putting into practice a methodology that will predict the best locations of aeroponic towers based on the collected environmental and spatial data.
- Considering the space requirements, tower configurations and layout schemes affecting the plant growth and system performance.
- To guarantee improved production and reducing water, energy, and space consumption.

- Present a solution to be used in the urban agriculture, green-house and controlled indoor environment.

replenished to the frontend and the users can see the optimized location of aeroponic towers in their farms.

IV. PROPOSED METHODOLOGY

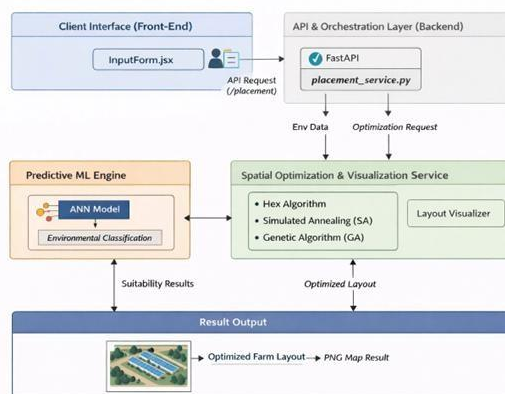
A. SYSTEM ARCHITECTURE

The proposed system is developed based on a modular and layered architecture in order to provide scalability, maintainability, and effective communication between the machine learning and optimization modules. The architecture is composed of four primary layers, which are the Client Interface Layer, the API and Orchestration Layer, the Predictive Machine Learning Engine, and the Spatial Optimization and Visualization Service. Client Interface Layer is the front-end part of the system, which is created with the help of Vite and React, and which offers the interactive and responsive interface. This layer enables the user to add farm size e.g. length, width, area, environment e.g. temperature, humidity, sunlight, water PH, air quality index and wind speed. It also allows users to choose the type of crop and the type of optimization algorithm to be employed to place towers like Hexagonal Lattice, Simulated Annealing or Genetic Algorithm. These inputs are gathered in the frontend in terms of input form component and submitted to the backend via REST API requests.

The API and Orchestration Layer constitute the back-end part of the system and is implemented as the FastAPI, which is a high-performance service based on the REST protocol. This layer serves as the main controller, which controls the interaction between the user interface, predictive machine learning module, and spatial optimization engine. Primary API endpoint is where the user gives the input parameters which are validated and sent to the relevant processing modules. The backend organizes the run of the predictive model and optimization algorithms, sums up the results and sends the processed output back to the frontend to be visualized.

The Predictive Machine Learning Engine will be tasked with the responsibility of determining whether the environment is suitable where to place crops by using a deep learning Artificial Neural Network model. Some of the environmental characteristics of the environment that the model takes into consideration include the type of crop, temperature, humidity, sunlight, water pH and air quality index as well as the wind speed to ascertain whether the conditions in that place are appropriate to the chosen crop. The neural network will have an input layer, two layers with multiple neurons and an output layer, which will give the suitability classification and a prediction confidence score. This forecasting makes sure, that spatial optimization is carried out in case of appropriate environmental conditions to grow crops.

The last level, which is the Spatial Optimization and Visualization Service, is concerned with the most efficient positioning of aeroponic towers within the farm space available. Several optimization schemes are applied to create efficient tower designs. The Hexagonal Lattice method employs the rules of geometry packing to maximize the use of space whereas Simulated Annealing employs probabilistic optimization in order to continuously optimize tower placement. The Genetic Algorithm also improves the layout by use of evolutionary processes that include selection, crossover, and mutation. Once the optimal arrangement has been decided on, the layout of the farm is created as a visual display indicating tower placement, grid orientation, and distribution of densities. The resulting spatial map is then



B. IMPLEMENTATION DETAILS

The proposed system of Intelligent Aeroponic Farm Optimization System was created based on the modular architecture that closely integrates machine learning-based prediction engine, spatial optimization algorithms, and visualization module. The system has been developed primarily around Python to provide the processing (backend) and machine learning, as well as with React and Vite to provide the interactive frontend interface. The backend services were implemented with FastAPI in order to provide efficient availability of the client interface based on the computation modules via the REST.

Predicting the suitability of crops was realized with the help of the Artificial Neural Network (ANN) by means of Multilayer Perceptron (MLP) model, which can be located in Scikit-learn library. The model has been based on the seven environmental features which are: crop type, temperature, humidity, sunshine days, pH level of water, air quality index (AQI) and wind speed. The type of crop is encoded with the help of a Label Encoder and numerical features are normalized with the help of StandardScaler to ensure that all the features have equal scores.

The neural network architecture is the following: the input layer will have seven features, the two hidden layers will contain 64 and 32 neurons respectively, and the output layer will have three neurons, which will relate to the suitability classes Poor, Borderline, and Ideal. Adam optimizer is used to perform the training and a maximum number of training iterations is 200. This data is stratified to 80:20 train-test split in which the data is evenly learning in all the classes.

The model artifacts, including the trained ANN model, feature scaler and crop encoder, are saved through the assistance of Joblib library. The artifacts are dynamically loaded at run time in such a way that they process user inputs. The prediction pipeline is to encode the type of crop, scale input features, and make predictions of suitability and select the crop with the highest score of suitability. Error handling is also provided to make sure that the system is stable in case the model artifacts are unavailable.

a. Special Optimization Implementation:

Spatial optimization module defines the optimal location of aeroponic towers which are to be installed in the farm area at the cost of fulfilling the spacing and boundary constraint. The optimization process facilitates three methods, such as Hexagonal Lattice Packing, Simulated Annealing (SA) and Genetic Algorithm (GA). The default optimization mechanism is the Genetic Algorithm although the Simulated Annealing is observed to be utilized as a refining mechanism.

1. Hexagonal Lattice Placement

The initial tower configuration is obtained using the hexagonal close packing method, which has a higher density compared to the square grid method. In this method, the vertical spacing between rows is obtained by the following formula:

$$\text{Row spacing} = s \times \sqrt{3} / 2$$

Where , s is the minimum spacing

2. Simulated Annealing Optimization

The position of the tower is optimized by the use of the simulated annealing of the probabilistic search of neighboring configurations. The algorithm begins with an initial temperature and reduces gradually through the aid of a cooling factor. These operations forming candidate solutions are adding, removing or relocating towers. In order to maximize the objective or with a probability that is determined by:

$$P = e^{\Delta/T}$$

the acceptance of a new solution is required.

Where,

D represents the variation in the objective function and T denotes the instantaneous temperature.

3. Genetic Algorithm Optimization

Genetic Algorithm is an algorithm that aims at finding near optimal tower positioning according to the evolution concepts. The algorithm maintains a population of layouts which are candidates and which it operates on via the use of selection, crossover and mutation. Tournament selection is used to select parent solutions and ordered crossover mutation and swap mutation are used to introduce diversity in the population.

The candidate solution fitness is the following fitness function of candidate solutions:

$$\text{Fitness} = \text{Number of valid towers placed}$$

C. ALGORITHMS USED

a. Random Forest

The random forest is an ensemble machine learning model that improves the classification results by combining a number of decision trees. All the trees are trained using the bootstrap sampling method on the training data set and a random subset of the features, which improves the robustness of the model.

Given a dataset :

$$D = \{(x_i, y_i)\}_{i=1}^{n_i}$$

where x_i represents the input feature vector and y_i denotes the class label, each decision tree produces a prediction $h_k(x)$.

The final prediction of the Random Forest classifier is obtained through majority voting among all K trees:

$$H(x) = \text{mode}\{h_1(x), h_2(x), \dots, h_K(x)\}$$

where H(x) represents the final predicted class.

In this study, Random Forest is employed to classify aeroponic crop suitability based on environmental parameters.

b. Support Vector Machine (SVM)

Support Vector machine is a learning supervised algorithm applicable in classification tasks and this is meant to find an optimum separating hyperplane among classes.

For a training dataset (x_i, y_i)

Where $y_i \in \{-1, +1\}$, the decision function is defined as:

$$f(x) = w^T x + b$$

where w =
weight vector b
= bias term.

SVM aims at maximizing the distance between classes and reducing classification error:

$$\min \frac{1}{2} \|w\|^2$$

subject to:

$$y_i (w^T x_i + b) \geq 1$$

The nearest data points to the separating boundary are termed as support vectors that define the best hyperplane.

c. Artificial Neural Networks (ANN)

The Artificial Neural Networks are mathematical models that are based on the biological neural systems. They are made up of networked neurons in the form of input, hidden and output layers. The network acquires patterns by updating weights in the course of training through the backpropagation algorithm.

For an input vector $x = (x_1, x_2, \dots, x_n)$

The neuron output is calculated as:

$$y = f(\sum_{i=1}^n w_i x_i + b)$$

where w_i = weight parameters b = bias term $f(\cdot)$ = activation function.

ANN models can establish nonlinear correlation between environmental factors and suitability of crops.

d. One-Dimensional Convolutional Neural Network (1D-CNN)

One-Dimensional Convolutional Neural Network A onedimensional convolutional neural network is a deep machine learning model that is used to provide significant features to sequential or structured data. The argument input sequence is convolved and x with a filter w is defined as:

$$s(t) = (x * w)(t) = \sum_a x(a) w(t-a) \text{ where}$$

' * ' represents the convolution operation.

Activation functions, pooling layers and fully connected layers are operated on the extracted feature maps to make the classification. A Softmax function is normally used to get the final output.

One-dimensional based CNNs have the ability to automatically discover high-level features within environmental parameters, which are useful in predicting the aeroponic crop suitability.

V. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, various machine learning and deep learning models are compared concerning their performance in predicting the suitability of various crops in aeroponic environments based on environmental parameters. Some of the models that are going to be considered in this study are the ones known as Random Forest (RF), Support Vector Machine (SVM), Artificial Neural Network (ANN) and One-dimensional Convolutional Neural Network (1DCNN).

Various dataset (1500, 2500, and 3000 samples) and training (500, 1500, 3000, and 5000) were used in the experiments to determine the effect of the scale of the dataset and training on the performance of the model.

The measures of evaluation applied in the study are Accuracy, Precision, Recall, and F1-Score.

1. Experimental Configuration:

The experiments were conducted with the supervised learning models, which were trained on the parameters of the environment considered in the aeroponic farming. The data was split into training and testing data to determine the predictive accuracy of both models.

Experiments to examine how training effort affects model performance were carried out using four settings of the iteration namely, 500, 1500, 3000 and 5000 iterations. Also, the three datasets sizes were employed:

1500 samples

2500 samples

3000 samples

Each model has the same conditions were used for training and evaluation to enable a fair comparison. The models' performance was evaluated using various classification performance measures such as accuracy, precision, recall, and F1-score.

2. Model Performance and Evaluation

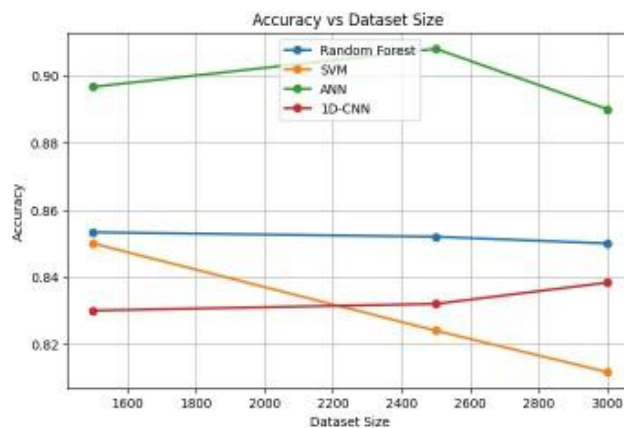
The results of the experiments reveal performance variation in the models under the evaluation with respect to the size of the dataset, and the count of training iterations. All in all, the Artificial Neural Network (ANN) had the greatest accuracy in most of the experimental environments.

ANN demonstrated the best results with 0.908 accuracy on 2500 samples after 500 iterations whereas random forest had a consistent accuracy of 0.85. The accuracy of SVM and 1DCNN was lower comparatively.

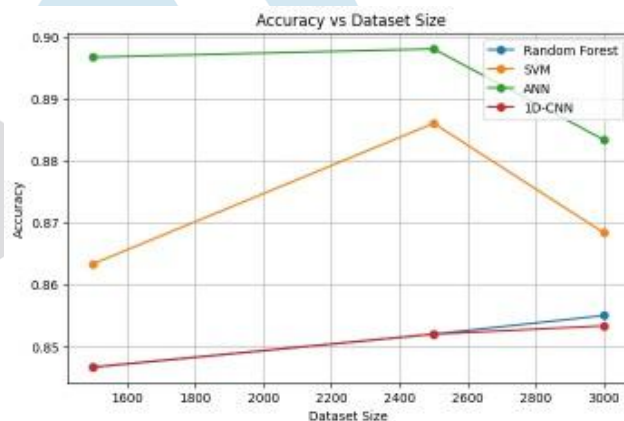
When the number of iterations was increased to 1500, it happened that the accuracy of SVM was improved, and it was 0.886 with 2500 samples and 0.855 with 3000 samples with the Random Forest. Nonetheless, ANN remained the most performing with an accuracy of nearly 0.898.

With 3000 iterations, the 1D-CNN model advanced significantly reaching 0.8917 accuracy using 3000 samples, with ANN showing stable high results.

Most models leveled off in performance after 5000 iterations. Random Forest stayed at the range of 0.85-0.86, SVM kept at 0.886, and ANN was still in the position of the most general performance.



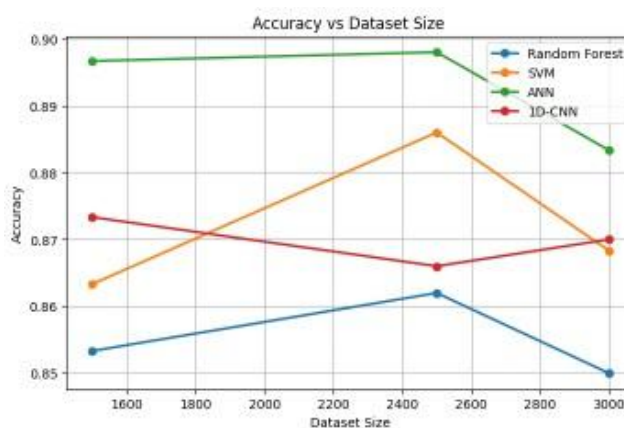
Graph 1: Accuracy vs Dataset Size for 500 iterations



Graph 2: Accuracy vs Dataset Size for 1500 iterations



Graph 3: Accuracy vs Dataset Size for 3000 iterations



Graph 4: Accuracy vs Dataset Size for 5000 iterations

The graphs above show the accuracy of the models as the size of the data set increases for different iterations.

3. Comparative Analysis

Comparing the four models reveals that ANN is always better than the other models in most of the experimental settings. This shows that neural networks are more successful in the nonlinear interactions of environmental parameters and crop suitability.

Random Forest was found to have stable and reliable performance but failed to perform the best. SVM was also good in moderate dataset sizes but poor when the dataset size was large.

According to the results presented by the 1D-CNN model, as the number of iterations and dataset size grew, the model provided promising results, which means that it can learn to represent meaningful features using structured input data.

In a nutshell, the findings indicate that the deep learning methods, especially ANN can be used to predict the suitability of aeroponic crops better than the conventional machine learning models.

4. Discussion

The experimental results suggest that the success of the model tends to increase with the size of the dataset, especially when dealing with deep learning models like ANN and 1D-CNN. These models also enable the acquisition of more representative patterns of the environmental parameters due to the presence of larger datasets.

Also, more training iterations can be used to enhance convergence and model stability, but the improvement of performance levels off after some point.

ANN outperformed all other models considered in this research, and it recorded the highest accuracy at 0.908 indicating that it is able to simulate a complex nonlinear relationship in the data.

These findings indicate that neural network-based models can be successfully used as predictive decision support systems in the aeroponic agriculture industry, which will allow making more precise recommendations regarding the suitability of crops.

VI. CONCLUSION

The project has had a chance to demonstrate how Artificial Intelligence and metaheuristic optimization techniques can be used in intelligent planning of aeroponic farms. The system is a holistic approach to the issue of productivity optimization of the farm under physical constraint in order to consider the environmental conditions by combining the machine-learning-based prediction of the environmental suitability as well as advanced spatial optimization techniques.

The Artificial Neural Network is effective in obtaining nonlinear relationships between environmental parameters and crop suitability and enables the differentiation of various conditions of cultivation. The generalization performance and the stability of training are ensured with the normalization of features and structured preprocessing. The trained model can be used to provide real-time crop recommendations through effective back-end inference.

The hybrid methodology is far more effective spatially on the optimization side. The first one is mathematically dense and produces a lattice, the lattice that is hexagonal and has a minimum search space. The layout optimization done by Genetic Algorithm also uses population based global search that keeps on adding towers as opposed to the deterministic placement. The system is supplied with the Simulated Annealing which is used to enable the local improvement process to be made in the probability fashion and the premature convergence to be avoided.

The algorithms are also verified to satisfy all the spacing and boundary requirements and also the realistic time of execution through run time and benchmarking. The modular design is not restricted, and more environmental parameters or the state of the art deep learning models can be introduced later.

Overall, the article describes the potential future of deep learning and evolutionary optimization in smart agriculture. Not only is this system maximizing the spatial efficiency of the system, but also ensuring the data-driven choice of crops, which can be appended to the solutions of sustainable, high-density and intelligent aeronics.

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