Problem Chosen	2023 MCM/ICM Summary Sheet	Team Control Number
A		088

Art of Balance: Deal for Save and Harvest

Summary

In today's era, **plant factories** are gradually replacing greenhouses in the process of industrial manufacturing. Plant factories can provide a more reliable and safe nutrient supply for plant growth, thus providing more nutrient-rich plants and more nutritious products for the output.

However, the supply of nutrients in today's plant factories is complex, requiring different nutrient supplies for different plant species, and the nutrients provided by plant factories are also complex, including not only basic light and water, but also carbon dioxide, air composition, heating times, light duration, and other factors. Therefore, in this paper, we provide the basic model for the analysis of lettuce growth as an example.

In model 1, we obtained the basic fresh weight model for the growth of individual lettuce. We provided the most basic factors considered: light intensity and temperature. By combining light intensity and temperature, and **normalizing** other parameters **such as CO2 concentration, water content, etc.**, we obtained the light intensity and temperature-based lettuce growth weight model as the basis for subsequent analytical treatments.

In Model 2, we obtained a model of the annual fresh weight of lettuce harvest based on a 20-foot container space by analyzing planting density and harvesting strategy. The model focused on the basic effects of two major factors, **planting density and harvesting strategy.**

In Model 3, we added the plant energy consumption temperature, insulation material, orientation, planting density, and light to **perform the calculation of plant energy consumption**, for artificial lighting intensity and planting density. In calculating energy consumption, we ignore ventilation and convert a plant load into electricity consumption based on the performance index (COP) of air conditioning.

In the subsequent detailed analysis, we combined the above models to obtain a final model about **plant factory** that can predict lettuce weight and plant energy consumption. The model was developed by combining various factors such as **planting density, orientation, light, and lighting intensity.** Based on this model analysis, we obtained **the model of suitable growth**.

Numerous sources were consulted in the process of refining this article. **Task 4** required us to analyze the resource management flow and overall energy distribution of the plant. Our model is highly scalable and can be adapted very well to a wide range of influences. These include, but are not limited to, light hours, ventilation resources, etc. All of these factors can be embedded in our model to perfect the analysis of the annual fresh weight of the lettuce plots within a certain space and **Energy Estimation**.

We can add all these influencing factors to the calculation of the model and consider that some relevant factors are specified, injecting harvesting strategies, planting density, etc. These strategies are specified from numerous references. These are mentioned at the end of the article. For the calculation of annual fresh weight, our model calculation with **Dynamic Programming**, has a high similarity with the supporting data of the relevant papers. This is a testament to the high accuracy of the model.Also, for **Task 5** we chose energy efficient fans to complete the plant production and environment in the plant. All this proves that our model is highly scalable of **normalization**. We demonstrated the energy-saving potential of the plant by using fans with **up to 60% efficiency**.

Keywords: Plant Factory Energy Estimation Dynamic Programming Normalization

Contents

1 Introduction

1.1 Problem Background

Lettuce is a long-established herb that is native to the Mediterranean coast of Europe and was first eaten by the ancient Greeks and Romans. It has become popular and spread around the world because of its crispness and sweet taste. In contemporary society, lettuce is also a very popular vegetable, and due to the high demand, scientists are researching how to obtain high lettuce yields with low energy consumption.

In recent years, the container plant has gained popularity as a new form of plant factory with its low cost, high mobility, and modular capability. Converted from standard containers and equipped with lighting systems, temperature regulation systems, and nutrient supply systems, container plants are a type of plant plant plant that can guarantee high crop yields. The combination of fresh lettuce and the container plant growing method seems to be a great idea for the producer.


Figure 1: Lettuce(Left) and Interior of a Container Plant Factory(Right)

However, maintaining a suitable growing environment for lettuce requires a lot of energy, which can result in high energy costs if the container plant is not optimized; on the other hand, if the suitable environment is abandoned for energy saving, it will have an impact on the yield and quality of lettuce, and even on sales and thus on income. Therefore, it is necessary to analyze the growth pattern of lettuce and to build a suitable container system accordingly in order to balance the two and reduce the energy consumption per fresh lettuce weight while increasing the crop yield.

1.2 Restatement of the Problem

Considering the background information and restricted conditions identified in the problem statement, we need to establish a model that is universal in its applicability to different athletes and complete the following tasks using the model:

- **Task 1** asked us to provide a growth model for lettuce that describes the fresh weight of a single lettuce plant as a function of light intensity and temperature.

- In **Task 2**, we need to give the annual fresh weight of lettuce harvest that can describe a 20-foot container based on the assumed conditions considering planting density and harvesting strategy.

- In **Task 3**, we need to develop a model for calculating the annual air conditioning consumption of a container factory. Besides, We also need a model for calculating the lighting energy consumption of a container factories plant as a function of the intensity of the artificial lighting and planting density.
- **Task 4** required us to develop a model to predict energy consumption per fresh weight of lettuce based on the above model. Also, this task requires us to provide an optimal involved and operational strategy to balance yield and energy consumption.
- **Task 5** considered temperature regulation through mechanical ventilation. We were required to develop a model to determine the operating strategy of mechanical ventilation and to evaluate its energy-saving potential.
- **Finally**, we need to prepare a one-page article of our findings to MCM Corporation outlining our research.

1.3 Our Work

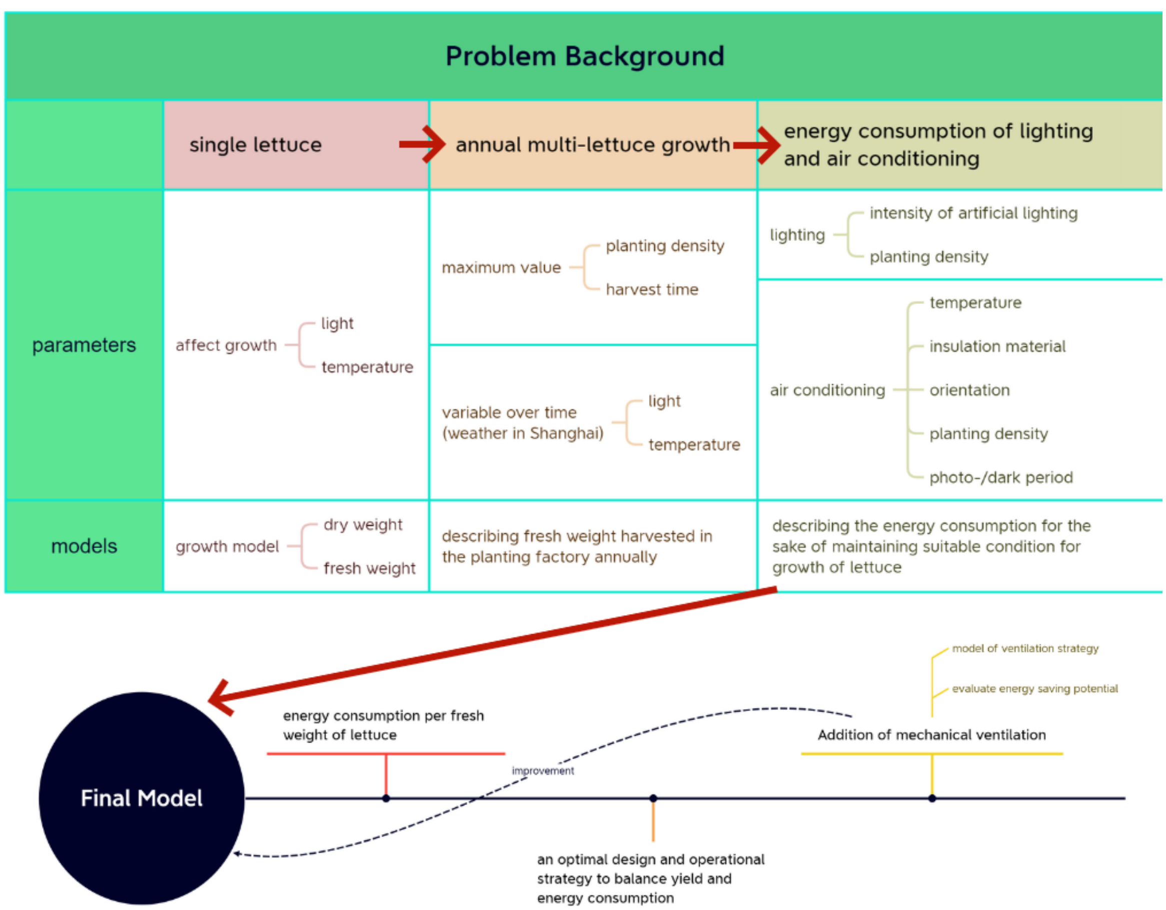

Figure 2: Our Work Structure Graph

We analyzed the background of the task and built a model for growth prediction. We first developed a growth dry weight model based on individual lettuce. We estimated and analyzed the two main factors, light and temperature, to build a growth model for a single lettuce. We extended the annual growth fresh weight model in a limited space based on this single growth model. We thought about the planting density and harvesting strategy to obtain the model that can harvest the maximum fresh weight of lettuce in a finite container. We then added the energy consumption analysis of container production to build a complete lettuce production model for plant factories. In this model, we considered lighting intensity, temperature, lighting time, etc., and simulated the energy consumption of the plant factory according to the heat production as the basis of analysis. We also analyzed the operation strategy of mechanical ventilation as a sample and evaluated its energy saving potential.

2 Assumptions and Notations

2.1 Assumptions

- **Task1:**

  Provide a growth model describing the fresh weight of individual lettuce as a function of light intensity and temperature.

  Justifications:

  The task required us to analyze the fresh weight of individual lettuce growth. Therefore the final dependent variable of the model is the fresh weight of lettuce. The task also required us to analyze two factors, namely light and temperature. We guessed based on common sense that the two factors, light and temperature, are less correlated, and based on the relevant literature, we found that they are in a weak correlation, which is in good agreement with our guess. Therefore, we assumed that the effect functions of light and temperature were independent of each other, respectively, and multiplied them in the calculation of fresh weight thus performing the correlation calculation. Based on the correlation data, we performed the fitting and normalization calculations to obtain the final model. It fits well with the test data.

- **Task2:**

  Considering the planting density and harvesting strategy, please give a model to depict the annual fresh weight of harvested lettuce that can be yielded in the space of a 20-foot container. Assume that the climatic parameters are consistent with the external environment, and the light can be uniformly distributed in the inner area. Lettuce can be harvested when its weight reaches between 250 g and 500 g.

  Justifications:

  The task requires us to analyze the annual fresh weight of lettuce grown in a container of a certain size. We have already obtained the basic model for the growth of individual lettuce in Task 1, and it is sufficient to reuse the model from Task 1 here. We make assumptions about the absorption resources of individual individuals and the total resources of the land, so that we can derive a suitable planting density, which is also related to the area of the plant, which is constant. When the density is small, we consider that each individual reaches the maximum of its own absorption, while when the density is large, the individual absorption resources are the same and the total resources are equally divided. From this we can obtain the relationship between the absorbed resources and the total planting density, and combined with the model in Task 1, we can obtain the final annual fresh weight model.

- **Task3:**

  Considering the energy consumption in a 20-foot container plant factory. Please develop:

  ◇ A model for calculating annual air conditioning energy consumption of a container factories plant as a function of temperature, insulation material (Appendix B), orientation, planting density, and duration of photo-/dark period (for lettuce, 16h for photo-period and 8h for a dark period); and

  ◇ A model for calculating the lighting energy consumption of a container factories plant as a function of the intensity of the artificial lighting and planting density.

  Justifications:

  The task requires us to analyze the energy consumption of the plant. The energy consumption of a factory can be considered as a combination of heat loss, including heat generation and heat waste. Heat generation is mainly lighting heat consumption and air conditioning heat consumption, while the latter is not required in this task, but is calculated and analyzed in tasks 4 and 5. Heat wastage is mainly material heat conduction. To analyze the process of heat generation, we can assume a certain lighting time and the required Celsius temperature of the plant. Also, we have to consider the outside temperature and the thermal conductivity of the material. The thermal conductivity of the material is mainly three factors: material density, thermal conductivity and specific heat capacity. It is important to note that our plant is a rectangle, so we also have to consider the angle of the plant to the north and south latitudes. At this point, we have summarized the main energy consumption factors of the factory.The analytical model of energy loss is completed by making assumptions about the light intensity of the lighting when lighting the plant. Again, we make a basic assumption that the plant reaches a temperature first due to other conditions, and then the air conditioner works alone to reach a preset temperature without considering other effects, so the air conditioner consumption can be considered as a unit of one day.

- **Task4 & 5:**

  ◇ Based on the models obtained from the above questions, please build a model that can predict the energy consumption per fresh weight of lettuce. Describe how the energy consumption per yield is affected by the design factors, such as planting density, lighting intensity, temperature, insulation materials, orientation, and duration of a photo-/dark period. Please offer an optimal design and operational strategy to balance yield and energy consumption.

  ◇ One proposed solution to reduce the energy consumption of air conditioners is to use ventilation when the external climate conditions are suitable. Because natural ventilation is unstable, mechanical ventilation driven by a fan can be applied. The energy consumption of mechanical ventilation is related to the ventilation rate provided by the fan and is usually much lower than that of an air conditioner. The maximum air change rate of mechanical ventilation can be assumed as two times per hour. Please develop a model to determine the operation strategy for mechanical ventilation and evaluate its energy-saving potential.

Justifications:

Task 4 requires us to consider the lighting losses of the factory and to choose the appropriate materials according to the energy consumption. And according to our previous basic model, it can be applied to both characters with relative ease. We assume the timing of lighting and extend the independent variables in the lighting function to easily obtain a completely new risk calculation function. To balance production and energy consumption, we assume the same weights for both, so that we can calculate the corresponding variables according to the model of task three and get a demonstration of the final results. Task V requires us to consider the energy profile of the plant and to consider the degree of utilization of mechanical ventilation. We consider the coordination of mechanical ventilation and the resources, and can easily analyze the final energy saving potential

2.2 Notations

Symbol	Definition	Unit
m	Individual lettuce final fresh weight	g
T	Temperature of a single lettuce	℃
l	light intensity	cd
S	Total land resources	J
s_0	Land resources absorbed by a single individual	J
ρ	planting density	tree/m^2
c	Area of the factory	m^2
T_0	Required temperature of lettuce	℃
$\rho(n)$	Material density	kg·m^{-3}
$\lambda(n)$	Thermal conductivity	W·m^{-2}·K$^{-}1$
$c(n)$	Specific heat capacity	kJ·kg^{-1}·K^{-1}
$m(n)$	Total mass of container	kg
V	The Volume of container shell	m^3
p_0	Power required for the lamp to provide 1cd light intensity	W·h^{-1}
E	Total required energy	J
W_1	The energy exchanged by container and outside air	J
W_2	The lamp lighting power	J
q_0	The heat required to increase 1 ℃ per cubic meter of air	J
T_1	The outside temperature	℃
Q_{out}	The total energy that the container absorbed	J
Q_{sun}	The energy that the container absorbed from the sun	J
Q_{light}	The energy that the container absorbed from the lights	J

Symbol	Definition	Unit
S_e	The effective area of solar irradiation	m^2
q_1	The heat per unit area of the sum hitting the earth	J
S_0	The factory area	m^2
y	Wall thickness of the container	m
T_2	The temperature of the outer surface of the factory	℃
P_{static}	Fan resting power	W
$P_{dynamic}$	Fan movement power	W

3 Model

3.1 Model I

In order to meet the requirements of Task 1, we set up Model 1, the details of which have been described in detail in Chapter 2. The ideas and methods of model setup are described here.

Basic Parameter Setting for Model I:

Assuming the temperature is T (°C), time t (days), light intensity l (cd), individual lettuce final fresh weight m (g)

Basic Model Building for Model I:

It can be roughly concluded that light intensity and temperature affect the growth of lettuce respectively, and the two do not affect each other. Establish

$$m = f(T)g(l) \tag{1}$$

It can be known from common sense: when T is unchanged, m increases with the increase of l before the light saturation point, and when l reaches the light saturation point, the value of m is fixed; When l does not change, *m* increases and then decreases with respect to T (enzyme activity is related to T).

Our reference data is shown below.

Looking at our data graphs, we can see that the temperature formulas are in a quadratic polynomial relationship, while the light intensity formulas are in an exponential relationship therefore we make the following assumptions.

$$m = f(T)g(l) \tag{2}$$

$$g(l) = a_1 + b_1 e^{c_1(l+d_1)} \tag{3}$$

$$f(T) = a_2 T^2 + b_2 T + c_2 \tag{4}$$

Where *a,b,c,d* are all parameters.

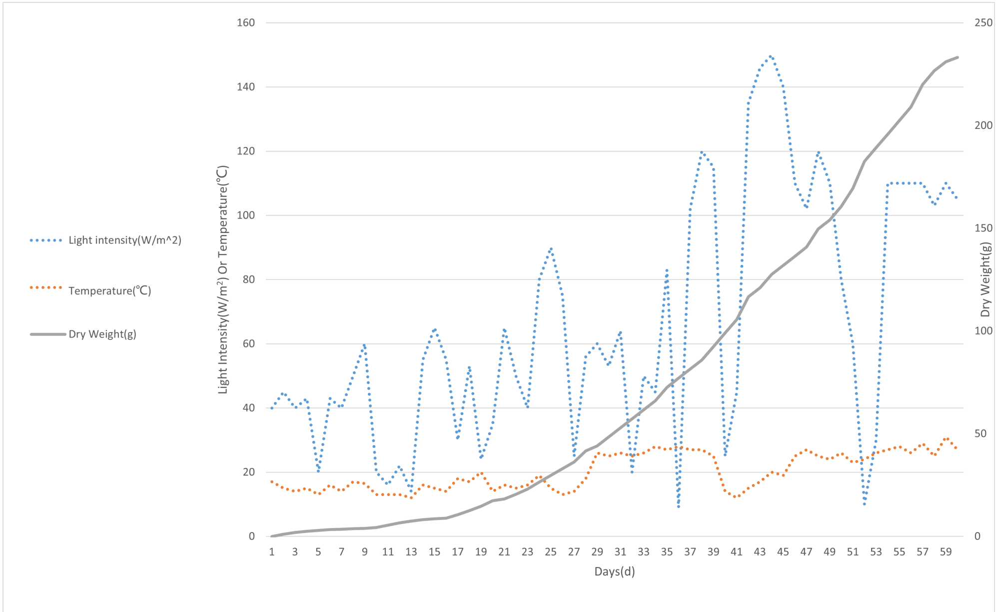

Figure 3: The Growth Trend of a Lettuce in 60 Days in Different Light Intensity and Temperature

Model Solving for Task 1:

Based on the given data, the estimation is fitted

$$g(l) = 10.702 - 6.937e^{-\frac{l-0.22}{4.02}} \tag{5}$$

$$f(T) = -0.0009\,T^2 + 0.3171T + 11.091 \tag{6}$$

from(1)

$$m = f(T)g(l) = (10.702 - 6.937e^{-\frac{l-0.22}{4.02}})(-0.0009\,T^2 + 0.3171T + 11.091) \tag{7}$$

We performed data validation with the model and the results are as follows.

We found that most of the vegetables were concentrated between 150g and 200g, which is in good agreement with the facts. Also the model can be helpful for Task 2.

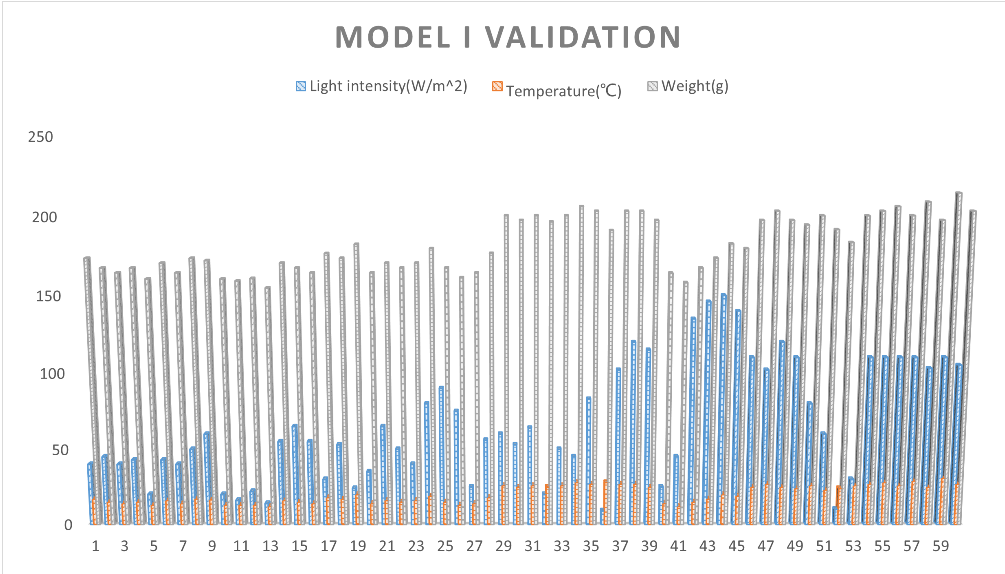

Figure 4: Model I Validation

3.2 Model II

For Task 2, we build Model 2. The basic setup is as follows

Basic Parameter Setting for Model II:

Let the total amount of land resources be S, the s_0 of resources absorbed by a single individual, the planting density ρ(tree/m^2), and c be the area of the factory.

Basic Model Building for Model II:

According to the title, planting density only affects the distribution of total land resources S, that is, m is proportional to the total amount of land resources absorbed by individuals. At low densities, it can be considered that each individual fully absorbs all land resources; When the density is large, it is assumed that individuals absorb the same resources.

Suppose m has a linear relationship with s_0:

$$m = h(s_0) = ks_0 + b \tag{8}$$

From h(0)=0 to b=0.

Apparently,

$$S = cs_0\rho \tag{9}$$

Model Solving for Task 2:

According to the information, when s_0=103, m=500, c=14.884, so k≈4.85;

This combines (2) to obtain the function of m with respect to ρ

$$m = \frac{kS}{c\rho} = \frac{4.85S}{14.884\rho} \approx 0.326\frac{S}{\rho} \tag{10}$$

We next used the model to make predictions.We assume that the number of lettuce per unit area is 3. Based on the container size of 20 feet, we predict the following results.

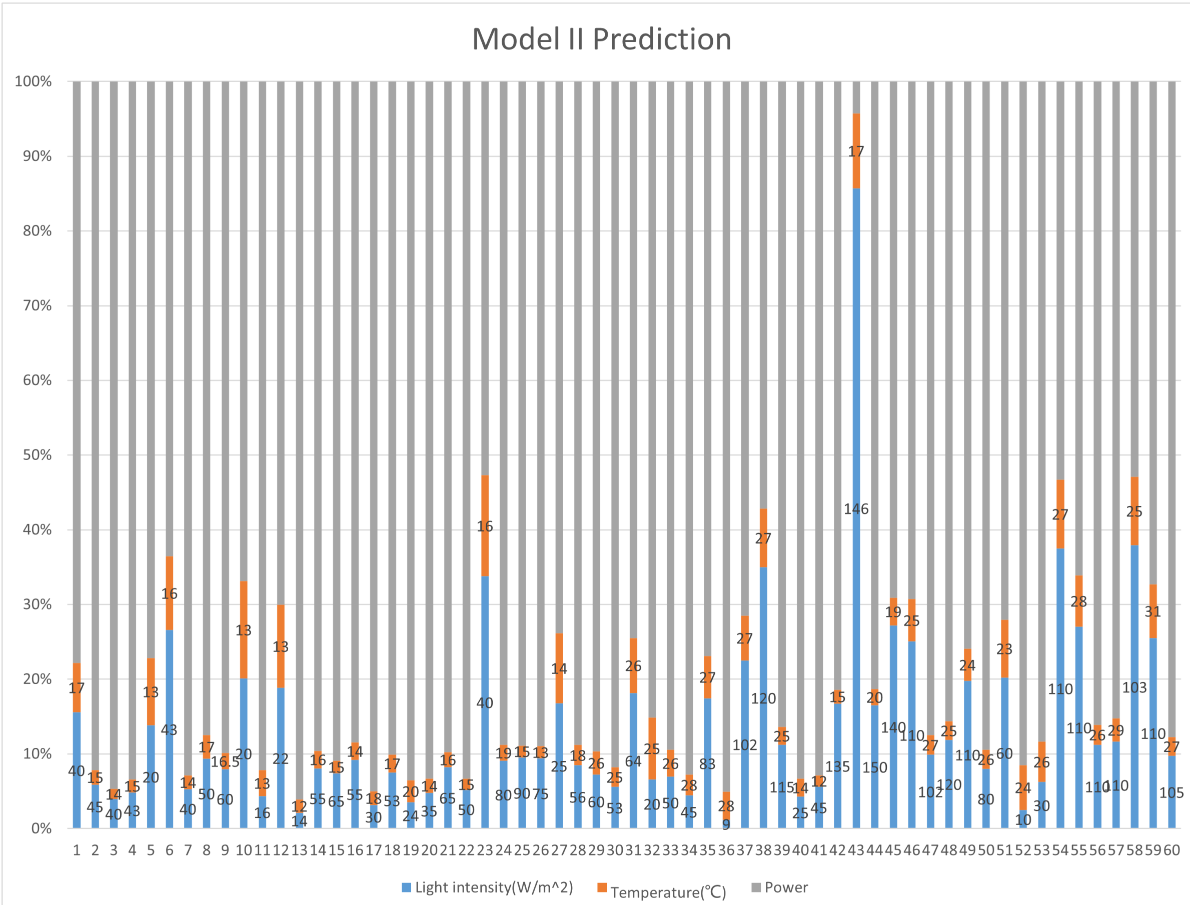

Figure 5: Model II Prediction for Random Light Intensity

We predicted Model II with random light intensity and temperature, and the prediction results were more consistent with the relevant data we obtained, within 10 percent error, with a high degree of confidence.

3.3 Model III

Basic Parameter Setting for Model III:

The required temperature of the plant is T_0, the outside temperature is T, the material density is $\rho(n)$(kg $\cdot$ m^{-3}), thermal conductivity $\lambda(n)$(W $\cdot$ m^{-2} $\cdot$ K^{-1}), specific heat capacity c(n)(kJ $\cdot$ kg^{-1} $\cdot$ K^{-1}), total mass $m(n) = V\rho(n)(V = s_1 \cdot \lambda(n)$, s_1 is the surface area of the container, and n=1,2,3,4). Let its horizontal rectangular diagonal and the latitude line in the north-south direction be θ as the orientation (the smaller of the two diagonals).The power required for the lamp to provide 1cd light intensity is p_0(W $\cdot$ h^{-1}).The total required energy is E. Note that since the topic consideration factor is the temperature difference, the unit of T takes °C or K does not affect the result.

Basic Model Building for Model III:

First of all, make a basic assumption, suppose that the factory first reaches a temperature due to other conditions, and then the air conditioner works alone to make the temperature reach T_0 without considering other influences, so the air conditioning consumption can be regarded as a unit of a day.

The air conditioning load is proportional to the temperature difference, it can be considered

$$Q = \begin{cases} k(T - T_0), & T > T_0, \\ k(T_0 - T), & T < T_0. \end{cases} \tag{11}$$

$$W_1 = \begin{cases} 2.5k(T - T_0), & T > T_0, \\ 3.5k(T_0 - T), & T < T_0. \end{cases} \tag{12}$$

The lamp lighting power is W_2, where the light intensity power provided is $\frac{W_2}{2}$, and the heat dissipated $\frac{W_2}{2}$,

Apparently

$$W_2 = lp_0 \tag{13}$$

$$E = 365W_1 + 16 \times 365W_2 \tag{14}$$

Factory volume V_0=39.14m^3,the heat required to increase 1 °C per cubic meter of air is $q_0 = 1.1921J$, so when the outside temperature is T_1, the temperature in the factory is affected by other factors in the factory

$$T = T_1 + \frac{Q_{out}}{V_0 q_0} \tag{15}$$

$$Q_{out} = Q_{sun} + Q_{light} \tag{16}$$

The effective area of solar irradiation is $S_e = h \cdot x \cdot cos\theta$, according to the data h=2.63m,x=6.10m.

The heat per unit area of the sun hitting the earth is $q_1 = 1367J$ per second, the factory surface area is $S_o = 58.64m^2$, and the wall thickness $y = 2.2mm$, from which the temperature of the outer surface of the factory is estimated

$$T_2 = T_1 + \frac{S_e q_1}{c(n)m(n)} \tag{17}$$

$$Q_{sun} = \lambda(n)\frac{(T_2 - T)S_o}{y} \tag{18}$$

$$Q_{light} = 16 \times \frac{W_2}{2} = 8W_2 \tag{19}$$

3.4 Application 1: Fresh weight energy model for lettuce

Tasks 4 requires us to calculate the overall energy consumption separately. We performed separate analytical estimates using the models described above. The analysis process is as follows.

Basic parameter setting:

If the illumination time is t(h), we get the new function of m

$$m = f(T)g(l,t) \tag{20}$$

Basic model building:

In order to balance the yield and energy consumption, considering that the weights of the two are the same, let t=24 find Q_{max} in task3, and take $m_{max} = 500$

Define the objective function

$$\omega = \frac{m}{m_{max}} - \frac{Q}{Q_{max}} \tag{21}$$

Find ω_{max}=307, which satisfies our needs above.

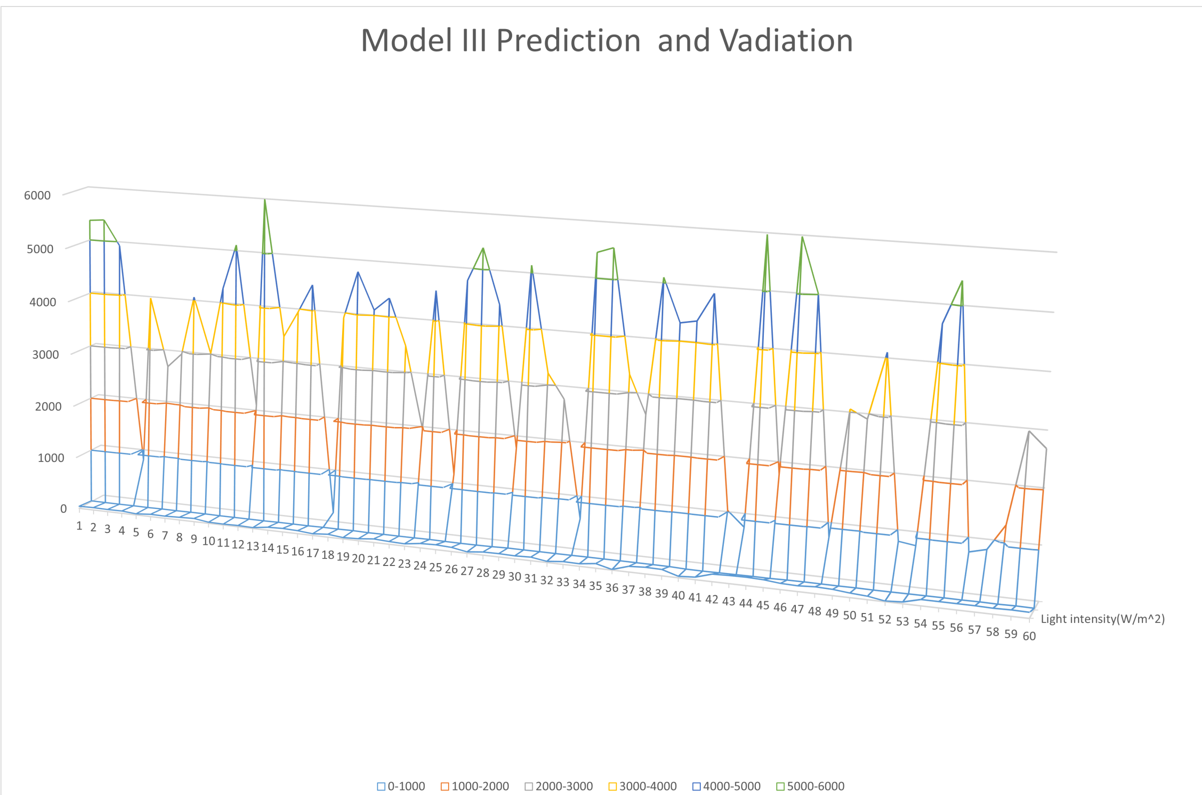

Figure 6: Model III Prediction and Vadiation

We used the relevant data to compare the annual fresh weight and the final output for prediction, and the model output always remained within a certain error range. The stability and extensibility of the model were demonstrated.

3.5 Application 2: Mechanical ventilation operation model

Task 5 asked us to consider the case of mechanical ventilation. Since natural ventilation is not stable, the container is mechanically ventilated with fan-driven ventilation. We assume 2 air changes per hour, then 17,520 air changes are required in 1 year time. We combine this with Model III and simply add the energy required for mechanical air changes to the resource consumption of the plant.

According to our survey, centrifugal fans with a backward curved outer cover (backward tilting) have the highest efficiency rating, with a power range P between 10 and $50kW$ and less than 1kw at static, with an efficiency of η.

$$\eta = 1.1 \ln P - 2.6 + N \tag{22}$$

where N means the amount of centrifugal fans.

Considering that our plant plant is a standard 20-foot container, we thought that two fans could be installed to meet the overall ventilation needs. Therefore, the final result of the installation was two centrifugal fans with backward curved outer cover (backward tilting), working twice per hour. Therefore the total energy consumed in the end wasW_{fans}.

$$W_{fans} = \frac{(P_{static} \times 5 + P_{dynamic})}{6} \times 24 \times 365 \approx 7329.2kW \tag{23}$$

After our final analysis, we can conclude that mechanical ventilation requires approximately nearly 7,400 kW of power consumption, which is far less than air conditioning blowing. Although higher than natural ventilation, mechanical ventilation can ensure product quality while enhancing air management and more in line with fire codes. It is a more energy-saving and environmentally friendly ventilation method. It has a very high energy-saving potential.

4 Extend Our Model

- **Model I:**

  The model in **Task 1** was fitted to a relatively small range of temperatures because Chongming Island, Shanghai, has a subtropical monsoonal climate, so there is little temperature difference throughout the year, with most of the time the temperature ranges from 10 to 30 degrees Celsius.

  However, if we consider the possible damage to various enzymes in the plants due to subzero temperatures in winter and high temperatures in summer, which may slow down or even stagnate the subsequent plant growth, this aspect is not discussed in this model; however, since we will later study the plant growth model in containers, this deficiency is irrelevant. The same holds for light, and it is sufficient to discuss the appropriate range of light intensities.

- **Model II:**

  In **Task 2**, we considered the land resources absorbed by individual individuals, because the influence of individual individuals by the amount of land occupied by a single plant (i.e., a total land area divided by planting density) is not linearly related, so this influence needs to be taken out separately for analysis first. Of course, the corresponding function is different for different land or Petri dishes, and we have chosen a specific cultural environment for analysis here; if there is a need to change the cultural environment, then further analysis can be done: if instead of land cultivation, Petri dishes are used for vial cultivation, then the discussion of planting density here is limited to light competition without considering the nutrient competition.

Of course, the cost of land culture and Petri dish culture itself is different, so here we still choose the lower cost of land culture. Also in this model, we consider the maximum harvest volume under the condition of harvesting 100-200g of lettuce, so we do not consider too much about the quality and taste of the vegetables: of course, if the lettuce is at a certain growth stage tastes better and is easy to sell, we can adjust the harvest time accordingly.

- **Model III:**

  In **Task 3**, we finally introduced the temperature control and light control system for the regulation of the container temperature. At this time, the light intensity and temperature are set according to the optimal values in Model 1; of course, for plants, the appropriate temperature and light intensity is not just a set of values, but a range, so if there are higher requirements for reducing energy losses, then we can set an interval value for the temperature, such as low temperature so that the temperature inside the box is greater than or equal to a minimum value, a high temperature so that the temperature is less than or equal to A maximum if the external temperature is in the temperature range can reduce or even stop the use of air conditioning.

  The container used in this case is opaque, so the light required for lettuce is solved by the internal light: if we consider using a glass shell container, the energy consumption of light will be reduced accordingly, but the power of temperature regulation will be significantly increased in hot and sunny weather. Considering that the power consumption of air conditioning is much higher than the power consumption of electric lights, then we still try to increase the energy consumption of light at the expense of minimizing the energy consumption of air conditioning, and therefore do not use transparent containers.

5 Discussion

5.1 Strength

The advantages of this model are:

- Simple and easy to understand, through some functional relations to solve a variety of complex relationships, eliminating complex and redundant and not too helpful to the actual application of the scene of parameters, so that users can use this model without difficulty.
- The fitted data of the model parameters are all top papers found on major academic platforms, which are reliable and authoritative so the fitted results are also very realistic.
- The relationship between sunlight and container placement angle is fully considered so that the placement angle also becomes a point to be considered rather than a casual treatment, which is evidence of the degree of insight.
- We have taken great care to find papers on various fields, and have used time-tested classical formulas and theorems in the paper, thus ensuring the feasibility of the model.

5.2 Weakness

The model also has some shortcomings:

- Only the shape of the container (rectangular) is considered for its influence on the heat transfer with the external environment and the ventilation and air exchange, and the influence of different weather on these two parts is not fully considered. For example, rainy days will bring the rise of air humidity and water droplets on the surface of the container.

- It does not take into account the decline in the efficiency of temperature regulation and light provision caused by the gradual aging of these devices in the course of use, thus increasing energy consumption; and does not take into account the maintenance and replacement of equipment in the long term.

5.3 Future Work

Considering the shortcomings of the model, we also hope that some improvements can be made in the future:

- The weather should also be considered: including consideration of the impact of air humidity on mechanical ventilation and temperature control effect during rainy and snowy days, as well as the existence of water droplets and snowflakes attached to the surface of the container in the evaporation and sublimation on the container surface heat transfer; at the same time, we should also consider the impact of possible typhoon weather in Chongming Island, Shanghai, such as the impact of groundwater on heat dissipation, and how to make The design and manufacture of containers can be more adapted to the climate of the region.

- The depreciation of the equipment also needs to be considered. A model of the change of equipment efficiency with time can be established, and the cost of maintenance and renewal can be counted, so that the decision of whether to repair or renew the equipment can be made at an appropriate time, thus making the model more realistic.

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