MCM 2023 Training Contest, Problem A
Plant Factory: An Artificial Fairyland

As a trend of modern facility agriculture, a *plant factory* is built to provide an artificial yet comfortable environment achieving optimal crop growth through the control of illumination, temperature, humidity, CO2, and nutrient solution delivery in a closed plant production system (CPPS). It can offer high-quality food with high productivity, meanwhile, reduce the usage of pesticides and fertilizer. In a plant factory, multi-layered cultivation shelves are installed such that we can plant crops on the floors of each layer while lighting systems are on the tops.

Recently, a new form of plant factory in a container has emerged, which has gained much popularity due to its low cost, high mobility, and modularization ability. Refitted from a standard shipping container, a *container plant factory* is further equipped with an intelligent climatization system and lighting system maintaining an artificial environment to satisfy the needs of multiple crops. Figure 1 exhibits photos of a typical container plant factory.

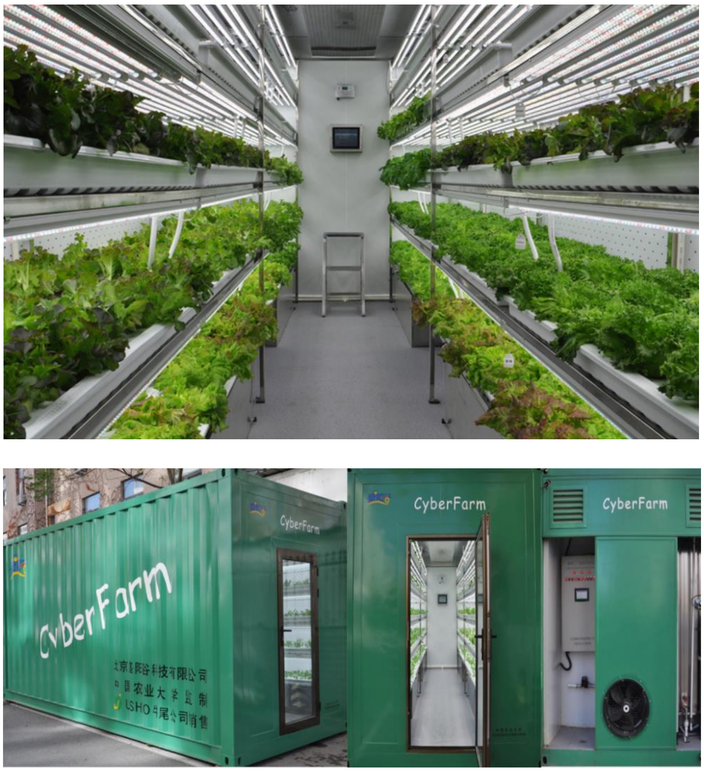

Figure 1. Interior and exterior of a container plant factory.

Plant growth is closely related to light and temperature. Suitable temperature and light can increase the plant's yield, whereas an improper environment negatively impacts plant growth. For plant factories, maintaining an appropriate environment requires extensive energy, whose consumption becomes a significant bottleneck restriction to future development. Because of their limited volume and large specific surface area, container plant factories need careful energy-saving design.

Energy consumption of plant factories mainly comes from lighting and air conditioning. Plant growth rate and energy consumption increase with light intensity in a particular range. A part of lighting energy dissipates as heat into the interior atmosphere of plant factories. It raises the internal temperature so that an air conditioner may be required for temperature control. Plant factories have two states (photo-/dark period), and the lighting is only used in the photo-period.

In addition to the heat generated by the lighting system, heat transfer between the external climate and the CPPS through the envelope (such as walls, ceilings, and floors) is another significant part of energy consumption for air conditioning. The container envelope is made of fixed materials of specific thermal properties (such as thermal resistance and absorptivity of solar radiation), whose properties will affect heat transfer efficiency. Additionally, the container's orientation will change its absorption of solar radiation. Meanwhile, the dynamic variation of exterior climate also affects air conditioning energy consumption. For example, in winter, lighting heat contributes to the reduction of the heating load, and appropriate insulation can prevent heat from escaping the container. However, in summer, if combined with significant lighting heat, high insulation will prevent internal heat gain from transferring to the outside and increase the cooling load.

It is also necessary to consider the planting density: If it is too low, the plant factory is not fully utilized. However, resource competition will emerge among plants if planting density exceeds a certain threshold, resulting in stunted growth or even premature senility.

Modern Container-Agricultural Management (MCM) Corporation hired your team to design a standard 20-foot (length * width * height: 6.10 m * 2.44 m *2.63 m) container plant factories with artificial light in Chongming Island, Shanghai, for growing lettuce. This project aims to increase crops' yield while reducing the energy consumption per fresh weight of lettuce. You are asked to choose appropriate envelope materials and the container's orientation and determine the closed system's optimal lighting power density, temperature, and planting density. Specifically, the following problems need to be addressed by your team:

- **Task 1**: Provide a growth model describing the fresh weight of individual lettuce as a function of light intensity and temperature.

- **Task 2**: 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.

- **Task 3:** 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.

  While calculating the energy consumption of air conditioning, we can ignore ventilation and convert a load of a plant factory to electricity use according to the coefficient of performance (COP) (Appendix B) of the air conditioning system. The air conditioning load consists of internal heat gain and heat transfer through the envelope (including absorbed solar radiation).

- **Task 4:** 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.

- **Task 5:** 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.

- As part of your solution submission, prepare a one-page article of your findings to MCM

Corporation outlining your research.

Your PDF solution of no more than 25 total pages should include:

- One-page Summary Sheet.
- Table of Contents.
- Your complete solution.
- One-page Article to MCM Corporation.
- Reference List.

Note: The contest has a 25-page limit. All aspects of your submission count toward the 25-page limit (Summary Sheet, Table of Contents, Reference List, and any Appendices). You must cite the sources for your ideas, images, and any other materials used in your report.

Appendix A: Reference

[1]. Graamans, L., Baeza, E., Van Den Dobbelsteen, A., Tsafaras, I. and Stanghellini, C., Plant factories versus greenhouses: Comparison of Resource Use Efficiency, Agricultural Systems, 160, pp.31-43, 2018.

[2]. Van Henten, E.J., Validation of a Dynamic Lettuce Growth Model for Greenhouse Climate Control, Agricultural Systems, 45(1), pp.55-72, 1994.

[3]. Chen Y.K., Huang Y.Y., Lan J., Wang T., Kang Y.X., Growth Model of Lettuce Cultivated by NFT based on Product of Thermal Effectiveness and Photosynthesis Active Radiation. Jiangsu Agricultural Sciences, 49(19):201-204+215, 2021. (Chinese)

[4]. Xu W.D. Effects of Different Light, Plant Density and Harvest Time on Yield and Quality of Lettuce in Plant Factory. Dissertation from Nanjing Agricultural University, 2015. (Chinese)

[5]. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook - Fundamentals

[6]. Al-Homoud, M.S., Computer-Aided Building Energy Analysis Techniques. Building and Environment, 36(4), pp.421-433, 2001.

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Appendix B: Description of parameters

1. The system loads (Q) for plant factories are converted to electricity use (E) following their respective coefficient of performance (COP) according to the formula:

$$COP = \frac{Q}{E} \tag{1}$$

where, cooling COP is set at 2.5 and heating COP is 3.5.

2. The efficiency of lighting system (the electric power dissipates as heat) is set as 50%.

3. Thermal properties parameter of optional insulation materials for container.

Table 1 Thermal performance of inorganic and composite thermal insulation materials.

Material	Density kg m^{-3}	Thermal conductivity W/m^2 K	Specific heat capacity kJ/(kg K)
Rockwool	120	0.041	1.22
Glass wool	40	0.04	1.22
Aerogel blankets	266	0.017	1.24
Aerogel vacuum panel	333	0.006	1.005

4. Air change rate (ACH): the number of times the total air volume in a room or space is completely removed and replaced in an hour.

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