Temperature Sum Based Hierarchical Optimization for Greenhouse Environmental Factors

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Abstract. In greenhouse production, more than 35% of the energy consumption was spent on greenhouse heating. Most greenhouse environmental control strategy is still static working point, and usually it can not adapt to outdoor weather changes so that the energy consumption in cold climate is enormous. In this study, based on the theory of temperature sum, a hierarchical optimization method for tomato was proposed. Based on the previous work, the economic benefit model of greenhouse control was summarized, and the economic benefit of each layer was solved by numerical method, so that we get a series of environmental set points for actuators, improving adaptability to extreme weather and saving 11% heating energy consumption in a week based on the energy consumption model. And carbon dioxide enrichment promoted photosynthesis rate and in the simulation the increment of production reached 248% based on Vanthoor's tomato yield model.

Introduction

After 30 years development, the greenhouse area in China is more than 300 million hm2, however, compared to developed countries, the energy consumption is too high this results in low economic benefit. In recent years, in order to solve the problem of greenhouse environment control, many kinds of control methods have been developed, such as PID control, fuzzy control, BP neural network control and so on [1,2,3], and obtained a lot of achievement. However these methods mainly focus on reaching the set points of environmental factors and often ignore the cost of the control process, although its regulation and control results ensures crop yield, but not necessarily achieve the maximum economic benefit. Although many important achievements have been made in greenhouse research [4], most of the greenhouse environmental control methods still use fixed set points control strategy, which is usually not adaptive to outdoor weather. Therefore, how to get the self-adaptive set points of greenhouse environmental factors is an important work to improve the economic benefit of greenhouse production.

Basing on the theory of temperature sum and taking tomato as an example, this research proposed a method to set up a series of feasible set points for greenhouse environmental factors dynamically. The result not only saves 11% energy cost, but increases the total production to 248% in the simulation.

Theory of Temperature Sum and Related Model

Theory of temperature sum. Crop growth requires a large amount of energy. A large number of greenhouse production experiences and researches show that the growth and development of crops usually need to complete the accumulation of certain energy, and for a particular crop from a specific stage to another the required energy amount is a constant [5]. That is to say crops need to be in a kind of temperature condition to accumulate energy so that they complete their certain development stages [6].In the area of agrometeorology, in a period that the average temperature meets certain rules, the sum of daily average temperature is known as temperature sum (accumulated temperature as well) and the unit of it is degree • day.

The model of tomato yield. Over the past decade, a variety of foreign and domestic tomato growth and yield models have been proposed for forecasting crop yield and predicting crop growth. In this study, the Vanthoor's model was used to simulate the production of tomatoes in greenhouse [8]. It has been widely verified in Europe and North America and the mechanism ensures the accuracy in yield and cost simulation. The photosynthetic rate (MC_{AirBuf}[mg / m^2 s]) is so complicated that we only introduce key steps in this research. The detailed calculation process and parameter selection are described in literature [14]:

1. Calculate the concentration of carbon dioxide in the stomata according to the concentration of carbon dioxide in the air. CO_{2Stom} [μmol {CO_2} mol^{-1} {air}].
2. The calculation of photosynthetically active radiation(PAR) absorbed by canopy PAR_{Can} [μmol {photons} m^{-2} s^{-1}].
3. The calculation of CO_2 compensation points Γ [μmol{CO_2} mol^{-1}{air}].
4. The calculation of the transfer rate of electrons J[μmol {e^-} m^{-2} s^{-1}].
5. The calculation of the gross photosynthesis rate P[umol {CO2} m^{-2} s-1], the photorespiration rate R[umol {CO2} m^{-2} s^{-1}] and the photosynthesis rate MC_{AirBuf}[mg m^{-2} s^{-1}].

Energy consumption model. The energy balance per unit area in the greenhouse can be described by the equation(1)(2)(3) [9,10,11]:

$$h_{\text{rad}} \mathrm{I}_{\text{Glob}} - \mathrm{K}_s \Delta T - K_l \Delta e - K_c \Delta T + Q_h - Q_m = 0 \tag{1}$$

$$Q_c = U_{gh} A_{gh} \left(T_{in} - T_{out}\right) W \tag{2}$$

$$Q_l = 0.373 V \left(T_{in} - T_{out}\right) W E \tag{3}$$

Where the heat transfer due to conduction Q_c[W] in equation (2) which is corresponding to $K_c \Delta T$ in equation (1) and the heat transfer due to ventilation Q_l[W] in equation (3) which is corresponding to $K_s \Delta T + K_l \Delta e$ in equation (1).The details of each parameter are listed on the literature [11].

If we define the efficiency of the heating system is η_{heat} and the greenhouse area is S_{gh} [m^2], the energy consumption E_{heat} [J / m^2] can be expressed as:

$$\mathrm{E}_{\text{heat}} = \int_{\text{init}}^{\text{end}} \frac{\mathrm{Q}_m + \left(0.373 V \left(T_{in} - T_{out}\right) W E + U_{gh} A_{gh} \left(T_{in} - T_{out}\right) W\right) / \mathrm{S}_{gh} - h_{\text{rad}} \mathrm{I}_{\text{Glob}}}{h_{\text{heat}}} \mathrm{dt} \tag{4}$$

CO_2 consumption model. The change of CO2 concentration in greenhouse is the integrated result of photosynthesis, respiration, ventilation and supplemental carbon dioxide. The balance of CO2 model is described in the equation (5) [9]:

$$h \frac{dCi}{dt} = C_g - C_{i,o} - \left(C_{gl} - C_{c,resp} - C_{s,resp}\right) \tag{5}$$

The details of each parameter are listed on the literature [9].And the consumption of carbon dioxide ECO2 [kg m^{-2}] could be deduced in the equation(6), the details of each parameter are listed on the literature [14]:

$$\mathrm{E}_{CO2} = \int_{init}^{end} C_g dt = 10^{-6} \times M_{co2} \times \int_{init}^{end} \left(P - R\right) \mathrm{dt} + \mathrm{h}\left(\mathrm{C}_{i,end} - \mathrm{C}_{i,init}\right) \tag{6}$$

Economic benefit model. The economic benefit of the greenhouse could be concluded as [14]:

$$\mathrm{Q} = Q_{cropyield} - Q_{fixed} - Q_{var} \tag{7}$$

Where $Q_{cropyield}$ (+) is the income from crops planted inside, Q_{fixed} (-) is the fixed expenses, and Q_{var} (-) is the variable expenses. The variable expenses mainly consists of expenses on CO2 injection and heating and cooling.So the economic benefit could be deduced into:

$$Q = q_{tom} h_{DMFM} \int_{init}^{end} MC_{BufFruit} dt - q_{energy} E_{gh} - q_{CO2} E_{CO2} \quad (8)$$

Where q_{energy} is the price of electricity[Yuan/J], and E_{heat} is the heating cost[J/m^2], q_{CO2}[Yuan/kg] is the price of CO_2, and the mass of injected CO_2 is E_{CO2}[kg/m^2], q_{tom}[Yuan/mg] is the price of tomato, η_{DMFM} is the conversion factor from dry mater to fresh weight, and DM_{Har}[mg/m^2] is the generated dry matter by tomatoes.

Introduction of fmincon function. The fmincon function which is built in Matlab is a commonly used method to deal with constrained optimization problems. It is a method based on sequence quadratic programming (SQP) and inner point algorithm [15]. The optimization problem of maximizing economic benefit is transformed into a minimum optimization problem by taking the opposite number of the objective function, and we use fmincon function to find the optimal sequence.

Hierarchical optimization for environmental factors

For the cherry tomato in greenhouse the whole production period lasts about 300 days, the accuracy of optimal value obtained by that is based on the theoretical model and it is difficult to ensure that those results in each control step are optimal as well. Since the majority of greenhouse energy consumption is due to heating, for the sake of energy saving, the temperature set point is particularly important. In this study, a hierarchical optimization method is proposed to get the optimal set points in every control step. One optimal is processed once in each layer where reliable data are taken into consideration, and the ideal set points for each timescale are obtained. The whole process is shown in Fig. 1:

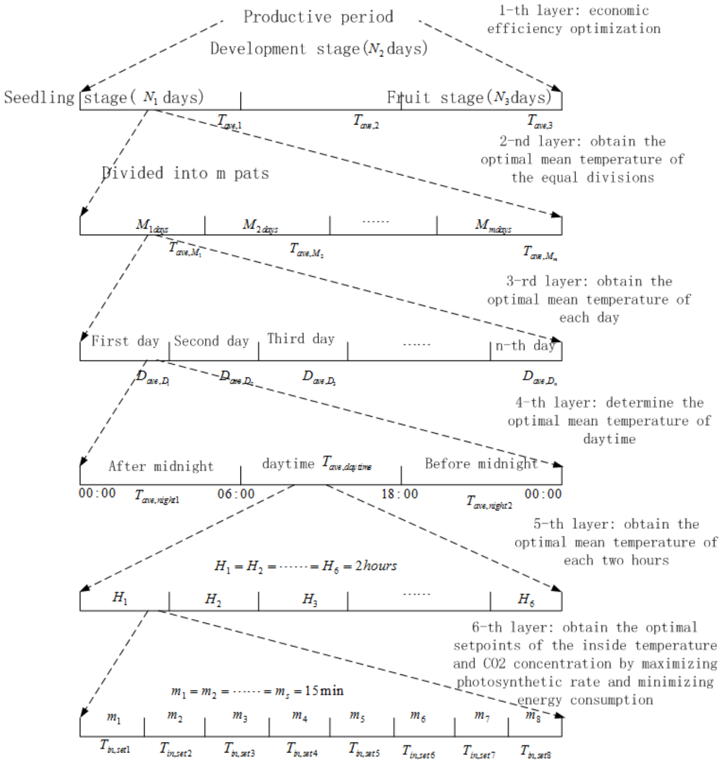

Fig. 1. the procedure of hierarchical optimization

1)The whole production period is often divided into three stages, seedling stage, development (vegetative) stage and fruit (generative) stage. And the average temperature of each growth stage is optimized with the objective of maximizing the economic benefit in the whole production period.

2) For the accuracy of weather forecast for a week each stage mentioned above could be divided into M weeks. The mean temperature of each week is optimized to maximize the economic benefits in

each growth stage. Because the first two steps are mainly based on the historical weather model, but currently there is no widely verified weather model, and we will set these parameters based on gardening experience.

3) Every week is divided into seven days, in order to maximize the economic benefit of the week, according to the weather forecast, we could optimize seven daily average temperature.

4) Every day is divided into three periods, the night after midnight, the daytime and the night before mid-night.

5) As the photosynthesis relates directly to the environment inside the greenhouse ,we need to optimize the mean temperature for each period (2 hours) in one day.

6) Every two-hour period should be divided into 8 15-minute step. Since the time scale of this layer is the length of a control step, which is directly related to process control, other environmental factors like carbon dioxide concentration and light intensity should be taken into consideration.

Simulation

The simulation data derive from a venlo type multi-span and multi- compartment glass greenhouse in Chongming center. Each compartment is 35 meters long, 25 meters wide and 7.5 meters high. Any simulation of the models above is simulated on these data, ensuring the accuracy.

Optimization of daily temperature. The result is listed in Table 1. By increasing the set points of temperatures of first two days, lower them in later three days, we not only ensure the temperature sum in a week, but also save much energy adapting to the extreme weather outside.

	Temperature outside [˚C]	Actual temperature inside[˚C]	Optimized temperature inside[˚C]
January 9, 2016	4.6	18.9	17.0
January 10, 2016	9	19	22.7
January 11, 2016	7.9	18.9	22.9
January 12, 2016	4.4	18.8	17.0
January 13, 2016	1.7	18.3	17.0
January 14, 2016	2	18.8	17.0
January 15, 2016	4	19.4	18.4

Table 1 result of optimized daily temperature

Optimization of 2-hour temperature. Some studies have shown that the DIF temperature at 6 ˚C effectively promotes the growth of tomatoes [16,17], according to that and the result in last step we could obtained optimal diurnal and night temperature. We use fmincon to solve the optimization problem, and the result is plotted in Fig. 2. The optimized night temperature is lower than actual one, in this situation we could save more energy at night.

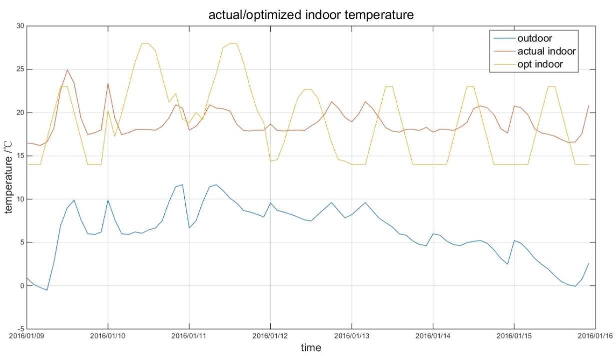

Fig. 2. result of optimized 2-hour temperature

Optimization of 15-minute temperature. In the optimization of 15-minute set point, a control step, the weather forecast and historical data are used to predict the radiation condition within two hours, and the objective is to maximize the economic benefit. The heating energy consumption has been considered in last step so the main cost is about carbon dioxide supplement. We use fmincon to solve the optimization problem, and the result is plotted in Fig. 3. It can be seen that after this optimization, the temperature is more definite than 2-hour temperature because of the specific radiation condition at different time. As shown in Fig. 3, CO_2 injection will promote photosynthesis, and make use of external solar energy and promote greenhouse production.

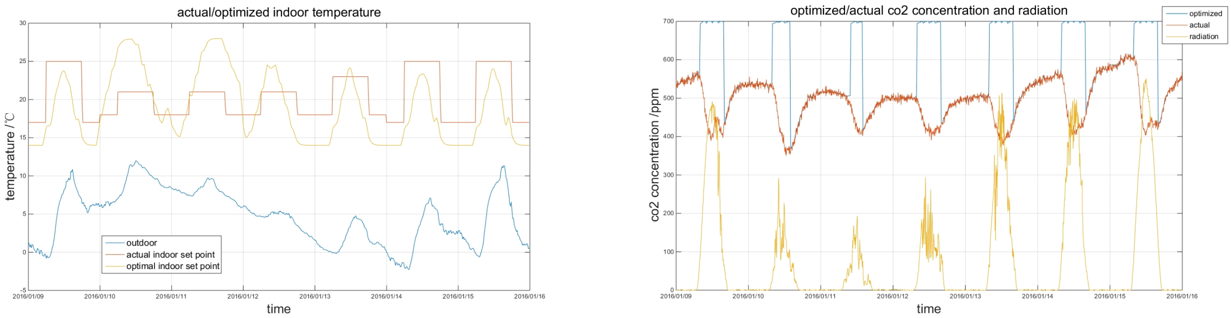

Fig. 3. result of optimized15-minute temperature

Result and Analysis. The daily energy consumption (MJ/m^2) for each step is shown in Fig. 4. When it is warm outside (January 10th and January 11th), the optimized energy consumption will be little higher than the actual, but when it is cold outside (from January 12th to January 15th), the optimized energy consumption will be lower than the actual, after the first step, the energy consumption in a week is reduced from 160.3 MJ/m^2 to 142.4 MJ/m^2, saving 17.9 MJ/m^2 and in other words 11%.

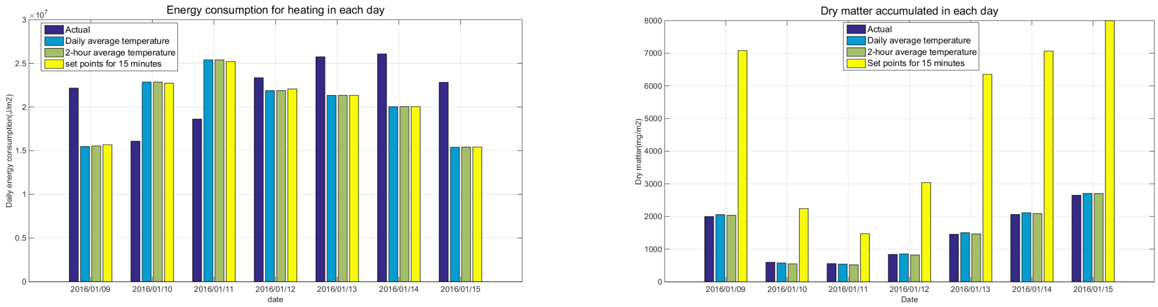

Fig. 4. the energy consumption and dry matter in a week

The daily dry matter (g/m^2) is shown in Fig. 4. On one hand, from January 10 to January 11, although the outdoor temperature is high, crops produce dry matter, this is because the light on these two days is too weak. On the other hand, the daily dry matter under the actual temperature conditions and that under the three optimization step were 10.1 g/m^2, 10.3 g/m^2, 10.2 g/m^2 and 35.2 g/m^2. In two previous conditions yield is not impacted significantly as the energy consumption reduced. And the dry matter yield is significantly increased due to the supplement of carbon dioxide in last step. Since the results are based on the model of Vanthoor, whether the application of the results can be achieved still needs further research and verification.

Conclusions

Most greenhouses still use a static set value to control the environment. It can not adapt to changes in outdoor weather, and often results in high energy consumption and higher expenses. For this situation, this study takes Tomato as an example, based on the theory of temperature sum, adopts a hierarchical recursive optimization method to set up the optimal set points of environmental factors dynamically. The simulation shows that the energy consumption can be reduced by 11% in one week. And by adding carbon dioxide the outcome can reach 248% of actual control strategy according to the yield model. The result of this optimization also has certain practical significance for the authenticity of data from Chongming center. And we're going to take artificial light into consideration in further research.

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