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Optimal control of LED light intensity in a plant factory

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Abstract: High energy cost of LED lighting is a key factor limiting big-scale plant factory production. In this paper, through optimal control computations, LED light intensity in a plant factory is optimized over time for different electric energy prices and lettuce crop prices. The dynamics of lettuce growth is considered by modifying a greenhouse lettuce growth model. Next, the modified dynamic model is calibrated through the experiment. The dynamic lettuce growth model, like most growth models, does not contain a mechanism that reflects the need for dark periods for proper growth. These are therefore enforced by disabling LED lighting during certain periods at night. Optimal control computations predict the profitability of plant factory production. Moreover, the optimal LED light intensity can be used in the actual production process. The optimal control computations reveal the influence of electric energy price and crop price on the profitability of growing lettuce in a plant factory. This information is highly valuable to growers, legislators, and governments.

Key Words: Optimal control, LED lighting, light intensity, dark time, plant factory

1 Introduction

With the limited availability of water and mineral nutrients as well as reduced availability of labour and accessibility to land and fertile soil, the increasing urban population demands a higher food production and production efficiency (Pennisi et al., 2019). Plant factory, or 'vertical farming', provides a promising prospect by increasing the efficiency of water and nutrients use through control of environmental factors and by limiting exchanges with the external environment (Benke and Tomkins, 2017; Tomkins et al., 2019). A simulation study with lettuce showed that vertical farms can increase the efficiency of land, water and nutrients use as compared to greenhouses located in Sweden, the Netherlands or the United Arab Emirates (Graamans et al., 2018). However, the high cost of elevated energy needs, mainly associated with electric lighting, is nonnegligible. According to Yang (2019), the energy cost of artificial lighting accounts for 60% of the total energy cost in a plant factory. Therefore, optimal use of artificial lighting remains a crucial factor in promoting plant factory production.

Optimal control has been widely researched in greenhouses (van Straten et al., 2011; Gonzalez et al., 2014; van Beveren et al., 2015; Seginer et al., 2017; Xu et al., 2018a). Some researchers also considered possible benefits of supplemental lighting in greenhouses through some form of optimal control (Ioslovich, 2009; Xu et al., 2018b; Xu et al., 2019). However, the studies on optimal controls often result in continuous supplemental lighting. According to Gaudreau et al. (1994), continuous supplemental lighting will increase the tip-burn occurrence in greenhouse lettuce. The tip-burn also occurs in plant factory lettuce production (Ahmed et al., 2020b). Moreover, research also shows that lettuce doesn't grow proportionally with continuous artificial lighting in a plant factory (Zha et al., 2019). Therefore, certain dark periods are necessary for plant factory lettuce production (Ahmed et al., 2020a). Unfortunately, most growth models lack mechanisms that reflect the need for dark periods for proper growth. Since, without artificial lighting, dark periods occur naturally, optimal control computations without artificial lighting do not suffer from this lack. Optimal control of plant factories, on the other hand, incorporates artificial lighting and will suffer from it. This explains the occurrence of optimal continuous artificial lighting (Xu et al., 2018b; Xu et al., 2019). To improve on this, in this paper dark periods do occur in our optimal control computations by disabling LED lighting during certain periods at night. According to Bergstrand et al. (2016), research conclusions on crop responses to the same artificial light quality can be contradictory. This phenomenon results from differences in crop variety, experimental setting, nutrient solution, and so on (Loconsole et al., 2019). Therefore, and because climate control is often performed through manual setpoint settings, only light intensity will be optimized in this research while other controls and settings will be conventional.

The major contribution of this paper is to investigate the profitability of plant factories with artificial LED lighting. To that end, a dynamic lettuce crop model is calibrated

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through experiment. Optimal control computations maximizing relative profit determine optimal LED light intensity including dark periods for different values of electric energy price and crop price. The relative profitability against the electric energy price and crop price is presented in Tables. These provide highly valuable information to growers, legislators, and the government in promoting plant factories.

2 Materials and methods

2.1 Experimental setup

The lettuce variety 'Tiberius' is chosen as the research object. Of these 16 plants per square meter are planted in a Deep Flow Technique way having 1 hour of nutrient solution circulation per day. During 21 days, 10 samples of dry weight are collected per week for crop model calibration purposes. The environmental setup and setpoint settings are shown in Table 1.

Table 1: Environmental setup and setpoint settings.

Environment	Light time (6:00-22:00)	Dark time (22:00-6:00)
Temperature (℃)	24	20
Relative humidity	70%	70%
CO_2 concentration (ppm)	1000	No control
Light intensity (μmol m^{-2} s^{-1}) (W m^{-2})	200(R/B=9:1) 45.865	0

2.2 Lettuce growth model

The lettuce growth model describing crop growth in a greenhouse as shown in Equations (1) and (2) is taken from Van Henten (2003). Physical meanings and values of different symbols are shown in Table 2.

$$\frac{dX_d}{dt} = c_{\alpha\beta}\varphi_{phot,c} - c_{resp,d}X_d 2^{(0.1X_T-2.5)} \quad (1)$$

With

$$\varphi_{phot,c} = \left(1-e^{-c_{pl,d}X_d}\right)\frac{c_{rad,phot}V_{rad}\left(-c_{co_{2,3}}X_T^2 + c_{co_{2,2}}X_T - c_{co_{2,1}}\right)\left(X_c - c_\Gamma\right)}{c_{rad,phot}V_{rad} + \left(-c_{co_{2,3}}X_T^2 + c_{co_{2,2}}X_T - c_{co_{2,1}}\right)\left(X_c - c_\Gamma\right)} \quad (2)$$

Table 2: Physical meanings and values of different symbols in Equations (1) and (2).

Symbol	Physical meaning	Value	Unit
X_d	Crop dry weight		kg m^{-2}
t	Time		s
$c_{\alpha\beta}$	Yield factor	0.544	
$\varphi_{phot,c}$	Gross canopy photosynthesis rate		kg m^{-2} s^{-1}
$c_{resp,d}$	Respiration rate in terms of respired dry matter	$2.65\cdot10^{-7}$	s^{-1}
X_T	Air temperature in the greenhouse		℃
$c_{pl,d}$	Effective canopy surface	53	m^2 kg^{-1}
$c_{rad,phot}$	Solar light use efficiency	$3.55\cdot10^{-9}$	kg J^{-1}
V_{rad}	Solar radiation outside the greenhouse		W m^{-2}
$c_{co_{2,1}}$	Temperature effect on CO_2 diffusion in leaves	$5.11\cdot10^{-6}$	m s^{-1} ℃$^{-2}$
$c_{co_{2,2}}$	Temperature effect on CO_2 diffusion in leaves	$2.30\cdot10^{-4}$	m s^{-1} ℃$^{-1}$
$c_{co_{2,3}}$	Temperature effect on CO_2 diffusion in leaves	$6.29\cdot10^{-4}$	m s^{-1}
X_c	Carbon dioxide concentration in greenhouse		kg m^{-3}
c_Γ	Carbon dioxide compensation point	$5.2\cdot10^{-5}$	kg m^{-3}

According to Van Henten (1994),

$$c_{rad,phot} = \varepsilon c_{par} c_{rad,rf} \quad (3)$$

With the physical meanings and values shown in Table 3.

Table 3: Physical meanings and values of different symbols in Equation (3).

Symbol	Physical meaning	Value	Unit
ε	The effect of photorespiration on the light use efficiency	$17\cdot10^{-9}$	kg J^{-1}
c_{par}	The ratio of photosynthetically active radiation to total solar radiation	0.5	
$c_{rad,rf}$	The transmission coefficient of the roof for solar radiation	0.42	

In a plant factory, $c_{rad,rf}$ becomes 1 because the LED light falls directly on the plant. Also c_{par} becomes 1 because LED light is a mixture of red and blue, and both are photosynthetically active radiation. V_{rad} in Equation (2) changes into U_{LED}, which means the controllable LED light intensity. Using the experimental data described in section 2.1, ε is calibrated to be $5.82\cdot10^{-9}$ kg J^{-1}. After calibration, the modelled lettuce growth matches the measured lettuce growth as shown in Fig. 1.

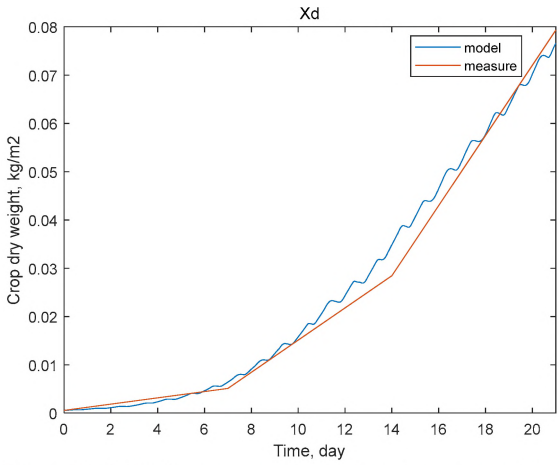

Fig. 1: Modelled lettuce growth matches the measured lettuce growth

2.3 Control objective

Taking the growers' economic perspective, profit obtained from growing crops is to be maximized. However, in this research, only crop dynamics are considered. This excludes dynamics and costs concerning plant factory climate control, except for energy costs required for LED lighting. This still matches our major objective to investigate the influence of electric energy price and crop price on profitability. Therefore, the following performance measure is maximized,

$$P = c_{pri} X_d\left(t_f\right) - \int_{t_0}^{t_f} \left(c_l U_{LED}\left(t\right)\right) dt \tag{4}$$

Physical meanings and values of the symbols in Equation (4) are shown in Table 4.

Table 4: Physical meanings and values of different symbols in Equation (4).

Symbol	Physical meaning	Value	Unit
P	Relative profit		RMB m^{-2}
c_{pri}	Price per lettuce dry weight	1034.55	RMB kg^{-1}
c_l	Price of LED lighting	$8.3\cdot10^{-8}$ - $2.553\cdot10^{-7}$	RMB J^{-1}
U_{LED}	Controllable LED light intensity		W m^{-2}
t_0	Start time	0	s
t_f	End time	$1.8144\cdot10^{6}$	s

The performance measure in Equation (4) maximizes what we will call the relative profit. So, the difference with ordinary profit is that except for the energy costs associated with LED lighting, other costs associated with growing crops and maintaining the plant factory climate such as cost of nutrient supply, labour cost, and energy cost to control temperature, humidity and CO_2 are ignored. One could take averages of these costs to approximate the full profit during the optimal control process. This study will focus on how the two parameters c_{pri} and c_l affect maximum relative profit described by Equation (4) as realized by optimal control of LED light intensity, i.e. U_{LED} in Equation (4).

A fresh lettuce price of 49.5 RMB kg^{-1} in a plant factory is obtained from JD.com. With a fresh/dry ratio of 20.9 (Van Henten, 1994), c_{pri} is set to be 1034.55 RMB kg^{-1}. According to bj.bendibao.com, the agricultural electric energy price varies in 0.2988 - 0.9192 RMB kWh^{-1}, which equals $8.3\cdot10^{-8}$ - $2.553\cdot10^{-7}$ RMB J^{-1}.

The current lighting setup produces 45.865 W m^{-2} radiation (see Table 1) requiring 82.915 W m^{-2} electric power. So, the transfer efficiency from electricity to light radiation is 55.3%. To cope with V_{rad} in Equation (2), controllable light intensity U_{LED} also employs the unit W m^{-2}. Because the upper limits of red and blue LED light intensity are 500 μmol m^{-2} s^{-1} and 360 μmol m^{-2} s^{-1} respectively in the current experimental setup, with an R/B = 9 ratio, the total LED light intensity has an upper bound of 115 W m^{-2}.

2.4 Optimal control

To introduce a dark period in LED lighting, a switching function multiplies the control input U_{LED}. This switching function switches between 0 and 1 as shown in Fig. 2. It assumes a dark period of 8 hours is beneficial to crop growth (Zha et al., 2019; Ahmed et al., 2020a).

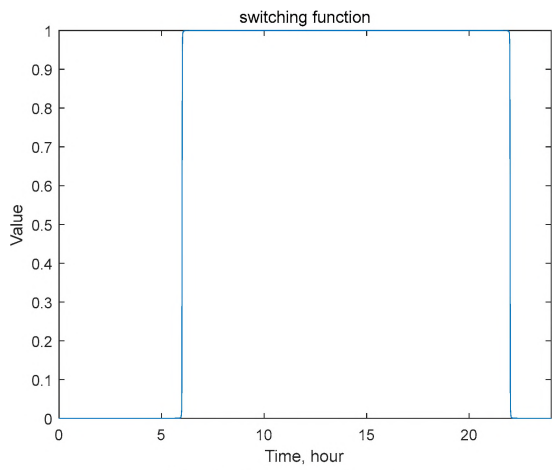

Fig. 2: Switching function

The environmental setup (Table 1), the lettuce growth model (Equations (1)-(3), Tables 1-3), and the control objective (Equation (4)), determine an optimal control problem. The optimal control toolbox PROPT, which is part of TOMLAB, a set of optimization tools for MATLAB, is used to solve the optimal control problem. This method uses pseudo-spectral collocation and polynomial approximations to very efficiently solve optimal control problems. The results from PROPT are further improved into digital optimal control form with the algorithm using the MATLAB function 'fmincon' (Xu et al., 2018a; Xu et al., 2018b; Xu et al., 2019).

3 Results and discussion

3.1 Fresh lettuce price from JD.com and agricultural electric energy price from Beijing

Taking the fresh lettuce price from JD.com being 49.5 RMB kg^{-1} and the agricultural electric energy price from Beijing being 0.2988-0.9192 RMB kWh^{-1}, optimal lettuce growth and LED light intensity are shown in Figure 3. This implies that if the harvested lettuce can be sold at the price shown in JD.com, optimal control directs the LED light intensity to the upper bound of the plant factory except during enforced dark periods (see Fig. 2). Further results are summarized in Table 5.

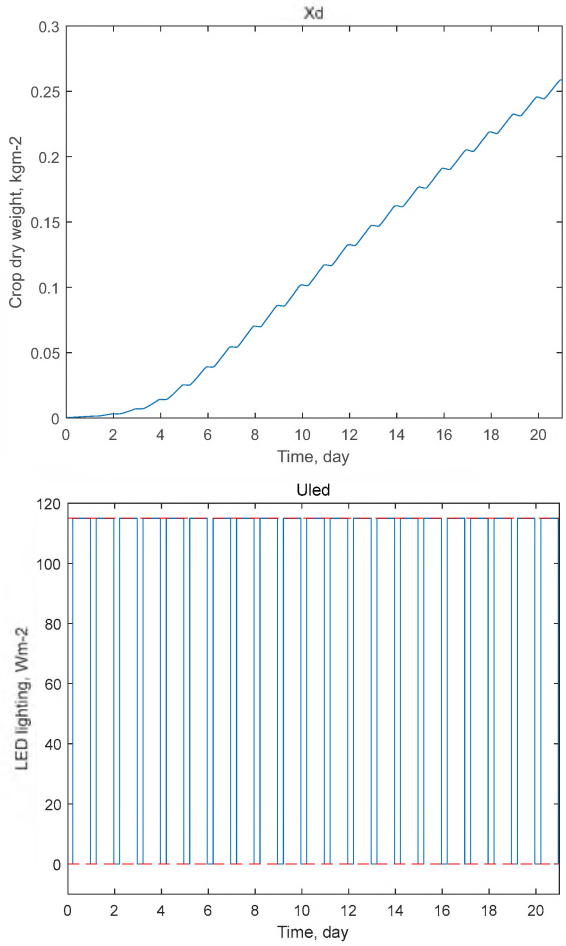

Fig. 3: Optimal lettuce growth and LED light intensity

Table 5: Optimal control results with the fresh lettuce price of 49.5 RMB kg^{-1}.

Electric price (RMB kWh^{-1})	Fresh lettuce harvest (kg m^{-2})	Revenues (RMB m^{-2})	Energy (kWh m^{-2})	Energy cost (RMB m^{-2})	Relative profit (RMB m^{-2})
0.2988	5.40	267.41	78.61	23.49	243.92
0.5	5.40	267.41	78.61	39.30	228.10
0.9192	5.40	267.41	78.61	72.26	191.89

3.2 Assuming LED light intensity reaching sunlight levels

Since the LED light intensity of 115 W m^{-2} is rather low it is interesting to see how optimal LED lighting performs under the assumption that sunlight levels can be reached. Take highest agricultural electric energy price of 0.9192 RMB kWh^{-1}, and assume the upper bound of LED light intensity is 2000 W m^{-2}. Optimal lettuce growth and LED light intensity, in this case, are shown in Figure 4. One should note that current LED lighting devices hardly allow these levels.

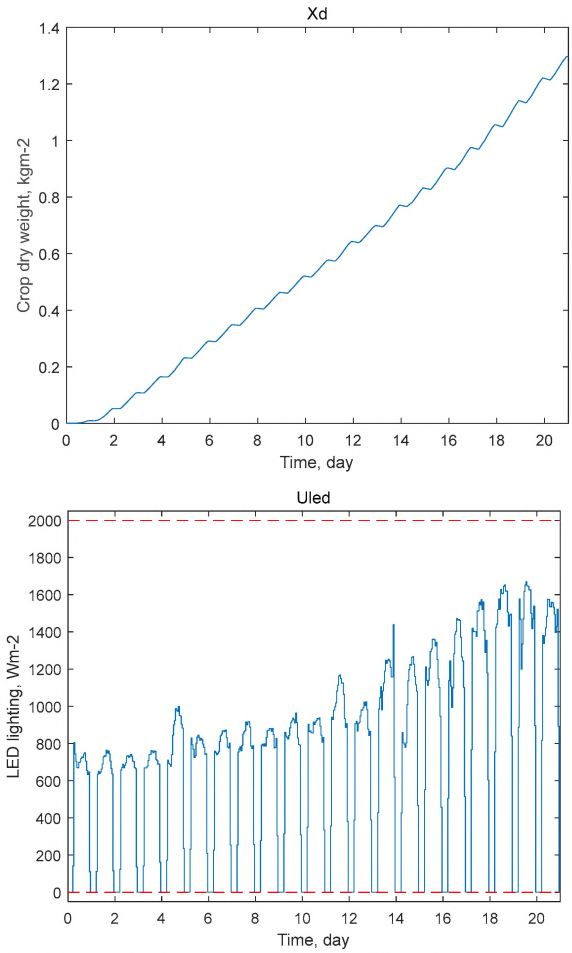

Fig. 4: Optimal lettuce growth and LED light intensity assuming LED light intensity reaching sunlight levels

The results imply that optimal LED light intensity increases with lettuce growth. This is in accordance with Ioslovich (2009). To avoid the fluctuations of the optimal control, one can take the average value of LED light intensity during the day as an approximation. In this way, the LED light intensity needs to switch only once each day.

3.3 Lettuce price from xinfadi.com and different electric energy prices

The average fresh lettuce price over the whole year 2018 as shown in xinfadi.com is 4.576 RMB kg^{-1} (95.6384 RMB kg^{-1} dry price), which is close to 1-10.8th of that in JD.com. This is a relatively low price because the lettuce is grown by farmers in the open field. The upper bound of LED light intensity is still taken 115 W m^{-2} just as it is in the experimental setup. When the electric energy price is 0.2988 - 0.9192 RMB kWh^{-1}, optimal control implies that it is not

profitable to supply LED lighting, which means plant factory production is not advisable. However, if the electric energy price reaches as low as 0.25 RMB kWh^{-1}, optimal LED light intensity increases in the first few days, and then it reaches the upper bound of LED light intensity since the 8th day as shown in Fig. 5. Further details are shown in Table 6.

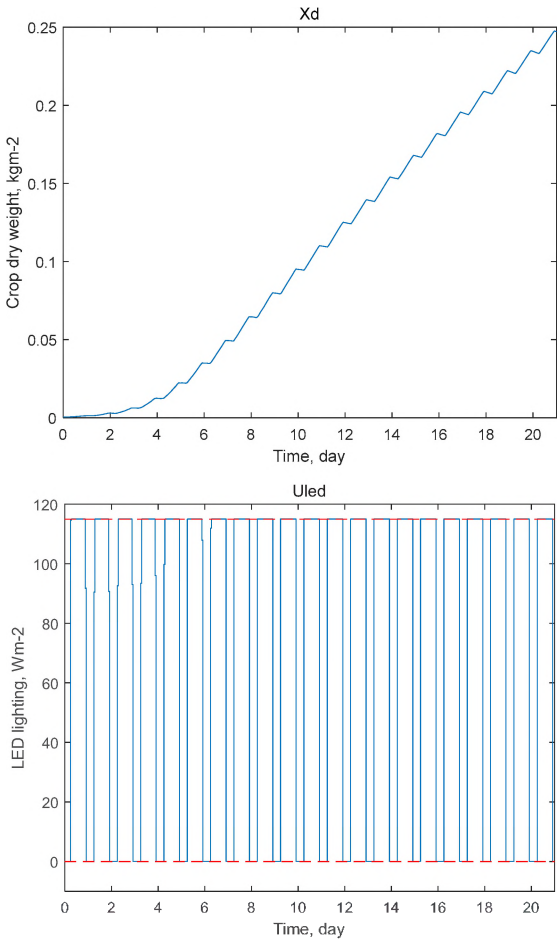

Fig. 5: Optimal lettuce growth and LED light intensity with the fresh lettuce from xinfadi.com

Table 6: Optimal control results with the fresh lettuce price of 4.576 RMB kg^{-1}.

Electric price (RMB kWh^{-1})	Fresh lettuce harvest (kg m^{-2})	Revenues (RMB m^{-2})	Energy (kWh m^{-2})	Energy cost (RMB m^{-2})	Relative profit (RMB m^{-2})
0.25	5.17	23.64	69.54	17.39	6.25
0.2988 - 0.9192	0.0068	0.031	0	0	0.031

If plant factory climate dynamics and other costs would also be included, the situation will most likely be more complicated. One of the interesting features of the optimal control approach is that it can handle these complications still enabling computation of maximal profitability.

4 Conclusions

1. According to the economic performance measure in Equation (4), plant factories are profitable when prices of energy are in the 'agricultural range' while fresh lettuce is 49.5 RMB kg^{-1}. Optimal LED light intensity reaches its upper bound every day except for dark periods. When fresh lettuce is 4.576 RMB kg^{-1}, plant factories are profitable when the price of energy is lower than 0.25 RMB kWh^{-1}. With the relatively low lettuce price, plant factories are not profitable when the price of electric energy is 0.2988 - 0.9192 RMB kWh^{-1}.

2. The economic performance measure in Equation (4) is optimistic in the sense that it only considers the energy costs associated with LED lighting, discarding other costs.

3. Economic analysis through the proposed method is highly insightful and relevant to growers, legislators, and governments when promoting plant factories.

4. Current crop models do not contain mechanisms requiring dark time. In this study, dark time was enforced by multiplying the control with a prescribed switching function.

5. Optimal control can fully exploit scientific knowledge on crops and plant factories through more advanced dynamic models. It provides a new way of evaluating profitability before production. Moreover, it enables real-time optimal control of LED lighting intensity instead of supplying fixed daily patterns.

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