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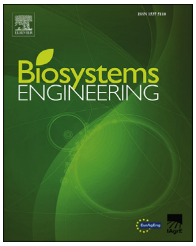

Research Paper

Optimal control of Chinese solar greenhouse cultivation

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The benefits of introducing heating, CO_2 supply, ventilation and LED lighting in a Chinese solar greenhouse are investigated. To that end, a two time-scale receding horizon optimal control system is assumed to accompany the introduction. The model of the Chinese solar greenhouse dynamics used by the optimal control system incorporates the effect of a north wall, present in any Chinese solar greenhouse. This wall stores heat during the day and releases heat at night to improve temperature. The optimal control system also takes control of a thermal blanket, that can be partly opened and closed to reduce heat loss to the environment. Apart from performing real-time optimal control, the optimal control system enables computation of improvements in terms of profit. Finally the feasibility of real-time implementation of the two time-scale receding horizon optimal control system on a personal computer is verified.

1. Introduction

The Chinese solar greenhouse (CSG) is a simple, effective construction to detach cultivation from external weather or to benefit from it. It has a roof made of plastic, glass or other materials and a thermal blanket that can be (partly) opened and closed to reduce heat loss to the environment. Furthermore a so-called north wall is present that stores heat during the day while releasing it at night. This is intended to improve temperature, especially to prevent too low temperatures at night (Li, 2005). This type of greenhouse is wide-spread in China. A schematic is shown in Fig. 1. Although a traditional CSG is designed to keep the greenhouse temperature above a certain level, based on "worst case" outside climate conditions, extra heating (Fang, Yang, & SUN, 2010; Wang, Bai, & Liu, 2002) is needed in some CSGs due to violations of these "worst case" climate conditions. Recent technological developments make it relatively easy to supply heat, CO_2, ventilation and artificial light in such a greenhouse. Moreover their supply can be performed by an advanced, two time-scale receding horizon optimal control system that is easily implemented on a personal computer (Xu, Du, & van Willigenburg, 2018). In this way the lower bound on greenhouse temperature, and also other constraints and objectives, can still be satisfied if "worst case" climate conditions are violated. By means of simulations, this paper shows that introducing these additional supplies, together with the advanced two

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Nomenclature

Symbol and Physical meaning with Values (Unit)	
U_b	position of the thermal blanket
$c_{ai,ou}$	heat transmission coefficient through the greenhouse cover, 6.1 (W m^{-2} °C^{-1})
$c_{rad,phot}$	solar light use efficiency, 3.55 10^{-9} (kg J^{-1})
α	influence of U_b on $c_{ai,ou}$, 2.4 (W m^{-2} °C^{-1})
$\varphi_{phot,c}$	gross canopy photosynthesis rate, (kg m^{-2} s^{-1})
$c_{pl,d}$	effective canopy surface, 53 (m^{2} kg^{-1})
X_d	crop dry mass, (kg m^{-2})
V_{rad}	solar radiation outside the greenhouse, (W m^{-2})
X_T	air temperature in the greenhouse, (°C)
X_c	carbon dioxide concentration in greenhouse, (kg m^{-3})
c_Γ	carbon dioxide compensation point, 5.2 10^{-5} (kg m^{-3})
$c_{co2,1}$	temperature effect on CO2 diffusion in leaves, 5.11 10^{-6} (m s^{-1} °C^{-2})
$c_{co2,2}$	temperature effect on CO2 diffusion in leaves, 2.30 10^{-4} (m s^{-1} °C^{-1})
$c_{co2,3}$	temperature effect on CO2 diffusion in leaves, 6.29 10^{-4} (m s^{-1})
U_l	electric power for generating supplemental artificial light, (W m^{-2})
$c_{light,phot}$	supplemental artificial light use efficiency, 6.256 10^{-9} (kg J^{-1})
ε	light use efficiency, 17 10^{-9} (kg J^{-1})
c_{par}	ratio of photosynthetically active radiation to total solar radiation, 0.5
$c_{rad,rf}$	transmission coefficient of the roof for solar radiation, 0.42
η_{light}	transfer efficiency of electricity to supplemental artificial light, 0.736
X_w	north wall temperature, (°C)
ρ_w	mass density of wall, 1700 (kg m^{-3})
C_w	specific heat capacity of wall, 1050 (J kg^{-1} °C^{-1})
V_w	volume of wall per greenhouse area, 0.168 (M)
c_{ws}	solar absorptivity of wall, 0.8
A_{in}	heat transfer coefficient of inner wall surface, 8.7 (W m^{-2} °C^{-1})
A_{out}	heat transfer coefficient of outer wall surface, 23 (W m^{-2} °C^{-1})
A_w	area of wall per greenhouse area, 0.28 (m^{2} m^{-2})
t	time, (S)
X_h	humidity concentration in greenhouse, (kg m^{-3})
$c_{\alpha\beta}$	yield factor, 0.544
$c_{resp,d}$	respiration rate in terms of respired dry matter, 2.65 10^{-7} (s^{-1})
$c_{cap,c}$	volumetric capacity of greenhouse air for carbon dioxide, 4.1 (M)
$c_{cap,h}$	volumetric capacity of greenhouse air for humidity, 4.1 (M)
$c_{cap,q}$	heat capacity of greenhouse air, 30000 (J m^{-2} °C^{-1})
$c_{cap,w}$	heat capacity of the north wall, 3.00 10^{5} (J m^{-2} °C^{-1})
U_c	supply rate of carbon dioxide, (kg m^{-2} s^{-1})
U_q	energy supply by the heating system, (W m^{-2})
U_v	ventilation rate, (m s^{-1})
$\varphi_{vent,c}$	mass exchange of carbon dioxide through the vents, (kg m^{-2} s^{-1})
$Q_{vent,q}$	energy exchange by ventilation and transmission through the cover, (W m^{-2})
$Q_{rad,q}$	heat load by solar radiation, (W m^{-2})
$\varphi_{transp,h}$	canopy transpiration, (kg m^{-2} s^{-1})
$\varphi_{vent,h}$	mass exchange of humidity through the vents, (kg m^{-2} s^{-1})
Q_{ws}	heat absorbed by the north wall, (W m^{-2})
Q_{win}	heat transferred from north wall to inside greenhouse, (W m^{-2})
Q_{wout}	heat transferred from north wall to outside greenhouse, (W m^{-2})
c_{leak}	leakage air exchange through greenhouse cover, 0.75 10^{-4} (m s^{-1})
V_c	carbon dioxide concentration outside the greenhouse, (kg m^{-3})
V_T	outdoor temperature, (°C)
V_h	outdoor humidity concentration, (kg m^{-3})
$c_{cap,q,v}$	heat capacity per volume unit of greenhouse air, 1290 (J m^{-3} °C^{-1})
$c_{rad,q}$	heat load coefficient due to solar radiation, 0.2
$c_{v,pl,ai}$	canopy transpiration mass transfer coefficient, 3.6 10^{-3} (m s^{-1})
$c_{v,1}$	parameter defining saturation water vapour pressure, 9348(J m^{-3})
$c_{v,2}$	parameter defining saturation water vapour pressure, 17.4
$c_{v,3}$	parameter defining saturation water vapour pressure, 239 (°C)
c_R	gas constant, 8314 (J^{-1} K^{-1} kmol^{-1})
$c_{T,abs}$	temperature in Kelvin at 0 °C, 273.15 (K)
P	profit, $(\$\ \mathrm{m}^{-2})$
t_0	start time of optimisation interval, (s)
t_f	end time of optimisation interval, (s)
$c_{pri,1}$	parameter defining price of lettuce, 0.954 $(\$\ \mathrm{m}^{-2})$
$c_{pri,2}$	parameter defining price of lettuce, 8.48 $(\$\ \mathrm{m}^{-2})$
c_q	price of heating energy, 3.366 10^{-9} $(\$\ \mathrm{J}^{-1})$
c_{co2}	costs of carbon dioxide supply, 22.26 10^{-2} $(\$\ \mathrm{kg}^{-1})$
c_v	price of ventilation, 2.226 10^{-6} $(\$\ \mathrm{m}^{-3})$
c_{el}	price of supplemental light, 1.325 10^{-8} $(\$\ \mathrm{J}^{-1})$
λ_s	co-state of crop dry mass, $(\$\ \mathrm{kg}^{-1})$
R_{Xh}	relative humidity, (100%)

time-scale receding horizon optimal control system, significantly improves the profit that is obtained from lettuce cultivation in CSG's.

Past research on cultivations in the CSG partly concerned hardware development (Ding, Wang, Li, & Wang, 2009). Ma, Han, and Li (2010) developed software to simulate and predict the thermal environment in the solar greenhouse. Sun et al. (2013) designed an active heat storage-release system incorporating a heat pump applicable to solar greenhouse heating. Wang et al. (2014) analysed the thermal performance