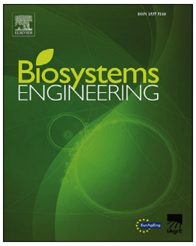
BIOSYSTEMS ENGINEERING 161 (2017) 188–199

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110



Research Paper

Day-to-night heat storage in greenhouses: 2 Sub-optimal solution for realistic weather

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ARTICLE INFO

Article history:
Received 24 October 2016
Received in revised form
14 June 2017
Accepted 22 June 2017

Keywords:
Greenhouse
Heat buffer
Optimal control
Self-adjusting co-state
CO_2 enrichment

Day-to-night heat storage in water tanks (buffers) is common practice in cold-climate greenhouses, where gas is burned during the day for carbon dioxide enrichment. In Part 1 of this study, an optimal control approach was outlined for such a system, the basic idea being that the virtual value (shadow price) of the stored heat (its 'co-state') could be used to guide the instantaneous control decisions. The results for *daily-periodic* weather showed: (1) The optimal co-state is constant in time. (2) The optimal solution is associated with minimum time on the storage bounds (buffer empty or full). With these conclusions as guidelines, a semi-heuristic procedure of optimisation for realistic (i.e. not strictly periodic) weather is developed. The co-state remains constant while the storage trajectory is *between* the heat storage bounds. It is gradually increased while the buffer is empty, and decreased when the buffer is full, attempting to push the trajectory away from the bounds, thus minimising the time that the buffer is idle. The main outcomes are: (1) No information about the future is required. (2) The algorithm changes the co-state automatically, producing the correct annual variation (high in winter and low in summer). (3) The predictions of yield and heat requirement compare favourably with practice. (4) The gain in performance achievable with the suggested method is probably 75% or more of the true optimum. (5) The procedure can be used in the design stage to determine the optimal buffer size and the usefulness of other modifications of the system.

1. Introduction

In cold-climate locations, where natural gas is burned during the day to enrich greenhouses with carbon dioxide (CO_2), water tanks (heat buffers) are often used to store the extra daytime heat for heating at night (De Zwart, 1996; Salazar, Miranda, Schmidt, Rojano, & Lopez, 2014). Considering initially a *daily periodic* weather, an optimal control strategy for such systems has been recently proposed (Seginer, van Straten, & van Beveren, 2017). The strategy, in which the co-state (virtual value, shadow price) of the stored heat is used to guide the instantaneous control decisions, was illustrated with *square-wave* and *natural* periodic weather sequences, as well as with *piecewise* and *simulation* solution techniques. The task now is to extend this approach to *realistic*, non-periodic, weather sequences.

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http://dx.doi.org/10.1016/j.biosystemseng.2017.06.023

Notation

[ground] greenhouse ground surface

Symbols

A	on-bounds adjustment rate of co-state, $\$\,J^{-1}$ [heat] h^{-1}
B	Bowen (sensible to latent heat) ratio
C	CO_2 concentration. mol [C] m^{-3} [air]
c	specific heat of air, J [heat] kg^{-1} [air] K^{-1}
F	global (solar) radiation flux, J [global] m^{-2} [ground] s^{-1}
f	sunlit leaf area index, m^2 [sunlit-leaf] m^{-2} [ground]
G	crop growth rate, mol [C] m^{-2} [ground] s^{-1}
H	heat flux, J [heat] m^{-2} [ground] s^{-1}
$\mathcal{H}$	Hamiltonian, \$ m^{-2} [ground] s^{-1}
I	infiltration rate, m^3 [air] m^{-2} [ground] s^{-1}
J	performance criterion (objective function), \$ m^{-2} [ground]
L	photosynthetic light flux, mol [PAR] m^{-2} [sunlit-leaf] s^{-1} = mol [PAR] m^{-2} [ground] s^{-1}
M	carbon content of crop, mol [C] m^{-2} [ground]
N	carbon growth rate of non-fruit organic matter, mol [C] m^{-2} [ground] s^{-1}
P	gross photosynthesis rate, mol [C] m^{-2} [ground] s^{-1}
p	gross photosynthesis rate at optimal temperature, mol [C] m^{-2} [sunlit-leaf] s^{-1}
Q	ventilation rate, m^3 [air] m^{-2} [ground] s^{-1}
q	temperature response of photosynthesis
R	respiration rate, mol [C] m^{-2} [sunlit-leaf] s^{-1}
S	stored heat, J [heat] m^{-2} [ground]
T	air temperature, K, °C
t	time, s
U	overall heat transfer coefficient across greenhouse cover, J [heat] m^{-2} [ground] K^{-1} s^{-1}
u_H	unit price of boiler heat, $\$\,J^{-1}$ [heat]
u_Q	unit price of ventilation, \$ m^{-3} [air]
u_Y	unit market price of produce (fruit) dry matter, \$ mol^{-1} [fruit-C]
X	CO_2 flux, mol [C] m^{-2} [ground] s^{-1}
Y	carbon growth rate of saleable fruit (yield), mol [fruit-C] m^{-2} [ground] s^{-1}
β	temperature exponent of respiration, K^{-1}
Γ	gain from installing a buffer ($\equiv J\{S_c\} - J\{0\}$), \$ m^{-2} [ground]
ε	efficiency of heat storage
η_{FH}	heating coefficient of global (solar) radiation, J [heat] J^{-1} [global]
η_{FL}	conversion factor solar energy to photosynthetic light, mol [PAR] J^{-1} [global]
η_{HX}	conversion factor heat to CO_2, mol [C] J^{-1} [heat]
η_{LX}	conversion factor light to CO_2 (photosynthetic 'efficiency'), mol [C] mol^{-1} [PAR]
ζ	fraction growth of saleable fruit out of total growth
κ	temperature correction coefficient, K^{-2}
Λ	co-state of S, $\$\,J^{-1}$ [heat]
ρ	air density, kg [air] m^{-3} [air]
σ	leaf conductance to CO_2, m^3 [air] m^{-2} [sunlit-leaf] s^{-1}
τ	transmissivity of greenhouse-cover to light

Subscripts

A	dissipated to atmosphere
B	supplied from boiler
c	installed capacity
F	due to global (solar) radiation
G	to greenhouse
i	indoor
max	maximum value
min	minimum value
o	outdoor
p	optimal for photosynthesis
r	at reference temperature
s	heat storage (in buffer)
T	total loss from greenhouse
V	by ventilation

Acronyms

FM	fresh matter (in fruit)
KWIN	KWantitatieve INformatie voor de Glastuinbouw
PAR	photosynthetically active radiation

The main conclusions of the previous study, which relate directly to the current task, are: (1) The co-state of the optimal solution for *periodic* weather is constant. (2) Simulation-optimisation produces optimal solutions for periodic weather. (3) The optimal co-state varies between seasons. (4) Performance is improved by minimising the time that the heat buffer is completely empty or full. These results are now used to develop a semi-heuristic approach to the more realistic problem of operation under actual weather. The general argument is as follows: It has been shown that the co-state of the stored heat remains constant while the buffer is not completely empty or full (storage not on bounds). It is also clear that while the buffer is completely empty or full it is ineffective in terms of operational storage. Hence a plausible strategy might be to simulate-optimise with a constant co-state while the storage trajectory is between the bounds, increase the co-state gradually when storage is on the lower bound (empty buffer) and decrease it when on the upper bound (full buffer). The adjustment of the co-state at the bounds is intended to push the trajectory away from the bounds, thus minimising the time that the buffer is idle.

In the following sections the system model is first briefly summarised, then applied to realistic year-long weather sequences to study some aspects of the control method. Finally, the effect of various parameters on the results is explored.

2. Methods

The essentials of the system model and method of optimisation are described in the next five sub-sections. A fuller