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Optimal Day-to-Night Greenhouse Heat Storage: Square-Wave Weather

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Abstract: Day-to-night heat storage is often practiced in cold-climate greenhouses. It is suggested to manage the heat storage by considering the co-state (virtual value) of the stored heat in the on-line optimization of the greenhouse environment. Examples worked out for a periodic square-wave weather show that a properly selected constant co-state can produce an optimal solution to the control problem. The optimal co-state is shown to change with time over the year. Maximizing the performance criterion can also be achieved by minimizing the time that the heat buffer is either completely empty or completely full.

Keywords: Greenhouse, Heat storage, Optimal control, Co-state, Constrained optimum, Time on bounds.

1. INTRODUCTION

In cold-climate locations, where natural gas is burned during the day to enrich greenhouses with carbon dioxide, water tanks (buffers) are often used to store the extra daytime heat for heating at night (de Zwart, 1996, Salazar et al., 2014). There are several possible configurations of these systems, but the focus of the present study is not on a particular configuration but rather on a methodology to optimally control such systems. The general idea is that the co-state of the stored heat, namely a virtual value attached to it, may be used to guide the instantaneous control decisions. If the co-state value is high, the system has an incentive to keep the buffer full, and vice versa if the co-state is low. A continuously empty or continuously full buffer is obviously useless as a storage device, meaning that the optimal co-state should have some intermediate value. It should be selected such that the daytime supply of CO_2, and hence the heat available for storage, is matched, as best as possible, with the nighttime heat requirement. As the CO_2/heat requirement ratio depends on season (high in summer and low in winter), the optimal co-state is expected to vary with time. In this study we explore the solution for just one (simplified) system configuration and a few square-wave periodic weather sequences. A somewhat similar approach to CO_2 enrichment, but using a different nomenclature, has been put forward by Aikman et al. (1997), who attached a 'dummy' value to CO_2.

2. MODEL

2.1 Heat and CO_2 balances

A simplified schematic of the system is presented in Fig. 1. It involves three compartments: Greenhouse (including crop), gas-fired boiler, and water heat-storage (buffer). The only state variable to be considered here is the stored heat, S.

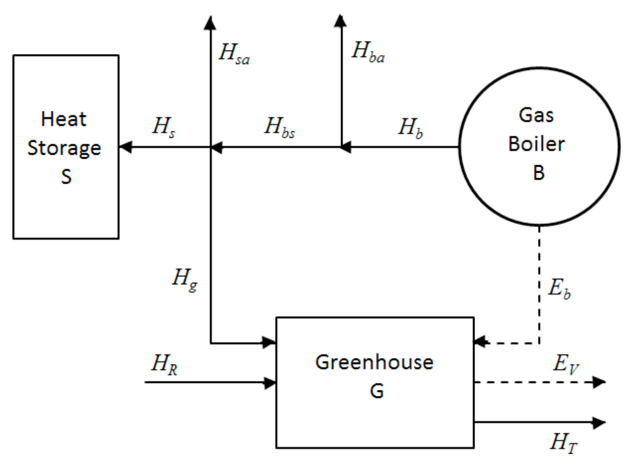

Fig. 1: Schematic representation of a greenhouse system with a gas fired boiler producing heat, H_b, and carbon dioxide, E_b. Some of the heat, H_{ba} and H_{sa}, is expelled or lost to the atmosphere, some, H_s, is transferred to a water-filled heat-storage (buffer), and the balance, H_g, heats the greenhouse. H_R is greenhouse solar heating ($H_R = \eta_{RH} R_o$), H_T is total greenhouse heat loss, and E_V is CO_2 loss by ventilation.

The model consists of three compartment balances: (1) heat-storage heat-balance, (2) greenhouse heat-balance, and (3) greenhouse CO_2-balance; Two junction balances: (4) 3-way junction heat-balance, and (5) 4-way junction heat-balance; and two process 'balances': (6) CO_2/heat equivalence ($E_b = \eta_{HE} H_b$), and (7) Storage heat-loss ($H_{sa} = [abs\{-H_s\} + H_s](1-\varepsilon_s)/(2\varepsilon_s)$). Of these, the first is an ordinary differential equation,

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$$\mathrm{d}S / \mathrm{d}t = H_s \ , \tag{1}$$

and the other six are algebraic expressions, to be used as constraints on the solution.

2.2 Control variables

Altogether there are 10 fluxes (Fig. 1) and 6 (algebraic) constraints, leaving 4 fluxes free as control variables. A sensible choice would be the ventilation rate, Q (affecting E_V and H_T), and the heat fluxes H_b, H_{bs} and H_s. Whenever the heat buffer is either empty or full, namely $\mathrm{d}S/\mathrm{d}t = 0$ (S is on its bound), the charging flux, H_s, must be zero. This removes H_s from the control vector, reducing by one the number of variables to be determined. The control variables are constrained as follows: $0 \le Q \le Q_c$, $0 \le H_b \le H_{b,c}$, $0 \le H_{bs} \le H_b$ and $-H_{s,c} \le H_s \le \varepsilon_s H_{bs}$, where the subscript c indicates the installed capacity. There is also a constraint on the stored heat, namely, $0 \le S \le S_c$.

The control fluxes Q and H_b are associated with unit costs, indicated respectively by u_Q and u_H. All other control fluxes may be considered cost-less, having been paid for by the cost of H_b. The remaining two fluxes, H_{ba} and H_g, can be derived from the control variables and the constraints.

2.3 Crop growth

In this study the crop (such as tomato) is assumed to be indeterminate and mature. Any additional growth (of leaves and fruit) is eventually harvested or pruned, such that the crop canopy remains essentially unchanged with time. Dry matter is, therefore, divided into three parts: (1) the 'unchanging' plants, represented by M, (2) the (cumulative) pruned leaves (plus stem and root elongation), and (3) the (cumulative) harvested yield.

The rate of growth is formulated as

$$G \equiv F + Y = h\{L_i, C_i, T_i\} f\{M\} \ , \tag{2}$$

where G and Y are the whole-plant and saleable fruit growth-rates; L_i, C_i and T_i are indoors light intensity, CO_2 concentration and temperature; h is growth rate per sunlit (projected) canopy area, and f is the sunlit leaf area index. The components F and Y are assumed to be proportional to each other, such that $Y = \zeta G$.

Further details of the model are similar to simplified models found in the literature (Aikman et al., 1997, Eq. 4; Seginer, 2003, Eqs. 23 to 26; Thornley & France, 2007 p. 290): The growth rate is the difference between gross photosynthesis and respiration:

$$h\{L_i, C_i, T_i\} = p\{L_i, C_i\} - r\{T_i\} \ , \tag{3}$$

where

$$p\{L_i, C_i\} = \frac{\eta_{LE} L_i \sigma C_i}{\eta_{LE} L_i + \sigma C_i} \tag{4}$$

$$r\{T_i\} = r_r \exp\{\beta(T_i - T_r)\} \tag{5}$$

and η_{LE}, σ, r_r, T_r and β are constants, estimated here from literature.

There are only two (temperature) constraints on the crop environment, namely $T_{\min} \le T_i \le T_{\max}$. There are no upper bounds on light and CO_2 concentration.

2.4 Greenhouse environment

A simplified greenhouse model is considered. In particular, terrestrial (long wave) radiation and latent heat fluxes are not explicitly specified, and heat capacities (except in the heat buffer) are ignored. The *outdoors* conditions are given in terms of just solar radiation, R_o, air temperature, T_o, and carbon dioxide concentration, C_o.

Indoors light is a constant fraction of R_o: $L_i = \tau \eta_{RL} R_o$. The indoors temperature is obtained by solving the greenhouse heat balance equation,

$$H_T = [U + \rho c(Q + I)(1 + B)/ B](T_i - T_o) \tag{6}$$

where U, ρ, c, I and B are considered to be constant (B differs between day and night). The indoors CO_2 concentration is determined by solving the CO_2 balance equation,

$$E_b - E_V - G = 0 \ . \tag{7}$$

2.5 Performance criterion and Hamiltonian

A period of time (e.g., one week) is considered, during which the environmental daily cycle repeats itself. The performance of the system, J, is measured in terms of the value of dry matter harvested as fruit, minus the cost of control, over one daily cycle, namely

$$J = \int_{day} (u_Y Y - u_Q Q - u_H H_b) \mathrm{d}t \ , \tag{8}$$

where u_Y is the price of tomatoes (in terms of its carbon content). Capital and labor costs are not considered. They are taken to be independent of the control. The Hamiltonian, $\mathbf{H}$ (Pontryagin, 1962), to be maximized at each point in time, is

$$\mathbf{H} = \Lambda_S \mathrm{d}S / \mathrm{d}t + u_Y Y - u_Q Q - u_H H_b \ , \tag{9}$$

where Λ_S is the co-state of S. In general, the co-state changes with time according to

$$\mathrm{d}\Lambda_S / \mathrm{d}t = -\partial \mathbf{H} / \partial S \ . \tag{10}$$

In the present problem the Hamiltonian is not a function of the state. Hence the co-state, Λ_S, is a constant, at least as