Receding Horizon Optimal Control of a Solar Greenhouse

R.J.C. van Ooteghem, L.G. van Willigenburg and G. van Straten
Systems and Control Group, Department of Agrotechnology and Food Science
Wageningen University, Bornsesteeg 59, 6708 PD Wageningen
The Netherlands

Keywords: solar greenhouse, model predictive control, temperature integration

Abstract

A solar greenhouse has been designed that maximizes solar energy use and minimizes fossil energy consumption. It is based on a conventional Venlo greenhouse extended with a heat pump, a heat exchanger, an aquifer and ventilation with heat recovery. The goal is to minimize fossil energy consumption, while maximizing crop dry weight, keeping temperature and humidity within certain limits and satisfying a temperature integral. To achieve this the aim is to implement a receding horizon optimal controller. This type of controller computes optimal closed loop controls based on a cost function and a greenhouse and crop model. In this paper simulations of a simplified version of this closed loop optimal control system are presented. It is found that the boiler use is reduced, thereby reducing fossil energy use. Gas use is decreased by 77% compared to a conventional greenhouse with optimal control.

INTRODUCTION

Intensive crop production in greenhouse horticulture in the Netherlands requires a high input of fossil energy of about 12.5% of the total national consumption. A new greenhouse design has been proposed, that maximizes solar energy use and minimizes fossil energy consumption. This solar greenhouse design is integrated with climate control to obtain optimal crop growth conditions. Model based receding horizon optimal control is used to maximize solar energy use, minimize fossil energy consumption and obtain optimal crop growth conditions. This closed loop optimal control strategy extends the open loop optimal control design presented by van Ooteghem et al. (2003).

Conventional versus Solar Greenhouse Design

A conventional greenhouse is heated by a boiler, which is also used to provide CO_2 for crop growth. The roof has a high transmission of solar radiation, but poor heat insulating quality. The greenhouse can be cooled by opening the windows, which also provides a means to decrease humidity.

The solar greenhouse has a roof with high transmission of solar radiation and better heat insulation, which will result in a higher crop yield and lower energy use. An aquifer is used to store solar energy. The aquifer consists of a warm- and a cold-water layer in soil. At times of heat demand, the greenhouse can be heated with less gas use with a heat pump and warm water from the aquifer. At times of heat surplus, the greenhouse can be cooled with a heat exchanger and cold water from the aquifer, while energy is harvested to use at times of heat demand. Compared to the conventional greenhouse, the solar greenhouse has more control possibilities:

- A heat pump to extract heat from the aquifer and supply heat to the greenhouse.
- A heat exchanger to extract heat from the greenhouse and supply heat to the aquifer.
- Ventilation with heat recovery, which can be used to decrease humidity with less heat loss than regular ventilation by windows.
- CO_2 supply independent of boiler operation, thus avoiding the need to use the boiler at times of CO_2 demand. Since it is the intention to use as little fossil energy as possible, CO_2 should be supplied by e.g. a power plant.

MATERIALS AND METHODS

For application of optimal control an accurate model of the controlled processes is necessary. The model needs to be sufficiently complex to include all processes in a broad working area, e.g. the temperature range should not be constrained to 0–30°C. Preference is given to a white model, since the internal variables have a physical meaning and can be easily interpreted. To limit computation time, the number of states has to be small.

Greenhouse and Crop Model

The greenhouse model used in this research has been developed based on the research by Van Henten (1994), De Zwart (1996), De Jong (1990) and Bot (1983). A photosynthesis model (Körner et al., 2002; Körner and van Ooteghem, 2003; Heuvelink, 1996; Farquhar et al., 1980) and an evaporation model (Stanghellini, 1987) are used to simulate the crop responses. The temperature and humidity bounds and the temperature integral have been developed by Körner (Körner, 2003; Körner and Challa, 2003). This model has been validated with greenhouse data, and was found to give an accurate description of the processes (van Ooteghem, 2003[A,B]). The model has been extended with the new solar greenhouse elements.

The Receding Horizon Optimal Controller

Using weather forecasts (SELyear, Breuer and van de Braak, 1989) and a model describing the dynamic behaviour of the greenhouse and crop in time, the influence of control changes on greenhouse climate can be simulated. The cost function to be minimized has the general form

$$J(u) = -\Phi(x,t) + \int_{t_0}^{t_f} L(x,u,t)dt \tag{1}$$

In this case it contains the costs of energy, loss of crop yield due to exceeding temperature or humidity bounds, crop yield and temperature integration. To this end the function L [cost·s^{-1}] is given by the sum of the penalties for temperature T_a, relative humidity RH_a, temperature integral S_T and energy consumption Q.

$$L(x,u,t) = L_{Ta}(x,u,t) + L_{RHa}(x,u,t) + L_{STI}(x,u,t) + L_Q(x,u,t) \tag{2}$$

The penalties for temperature, relative humidity and temperature integral are given by

$$L_x(x,u,t) = \begin{cases} c_x \cdot (x(t) - x_{\min}) & x_{\min} > x(t) \\ 0 & x_{\min} \le x(t) \le x_{\max} \\ c_x \cdot (x_{\max} - x(t)) & x(t) > x_{\max} \end{cases} \tag{3}$$

where c_x are the cost associated with exceeding the boundary values $x_{\min}$ or $x_{\max}$ of state x. Further penalties are given for energy consumption

$$L_Q(x,u,t) = c_Q \cdot (Q_{boil} + Q_{hp} - \eta \cdot Q_{he}) = c_Q \cdot Q_{sum} \tag{4}$$

where Q_{sum} [W·m^{-2}] denotes energy used by the boiler and the heat pump and recovered by the heat exchanger. An efficiency factor $\eta = 0.7$ is introduced for the heat exchanger, since only a part of the recovered energy can be reused.

The terminal costs Φ are determined by the yield W_f and the temperature integral (described in §3), at the end of the control horizon t_f.

$$\Phi(x,t) = c_{Wf} \cdot (t_f - t_0) \cdot (W_f(t_f) - W_f(t_0)) - c_{TI} \cdot |\Delta T_{a\_TI}(t_f)| \tag{5}$$

In table 1 the values used in the cost function are given. There is no penalty on the CO_2 concentration; the bounds are used for the proportional controller. The value of c_Q corresponds to a cost of 0.2 per m^3 gas. The boundary values for temperature and temperature integral are taken from Körner (2003).

During each sampling period a receding horizon controller computes optimal control trajectories over the control horizon t_f. From the optimal control trajectories only the first control value is applied to the process. Then measurements are performed again to estimate the next state of the greenhouse climate (and ideally also the crop). Then the optimal control calculation is repeated starting from the next estimated state over the new time horizon, shifting time over one sampling interval (receding horizon). The feedback thus achieved limits deviations between model predictions and measurements.

Because a receding horizon optimal controller solves an optimal control problem during each sampling period, the simulation of the associated optimal closed loop control system is very time consuming in general. To drastically limit the simulation time, the optimal control problems to be solved by the receding horizon optimal controller are highly simplified using discretization of the control space. The two control inputs (vp_h, Ap_{csd}) are discretized as follows. The possible values of vp_h are restricted to {-1 -0.5 0 0.5 1 1.5 2} and of Ap_{csd} to {0 0.5 1 1.5 2}. These values are applied over the full control horizon of the corresponding optimal control problem with one exception. If during the simulation the boundary values (T_a, RH_a) are exceeded, another discrete control value is used based on model knowledge. The control input combination with the lowest cost is chosen. As a result the global solution of the simplified optimal control problem is obtained after only 35 simulations.

1. Control Horizon and Sampling Period. Control horizons ranging from one hour up to several days are used by Shina and Seginer (1989) and Van Henten and Bontsema (1991). These long horizons are used because crop growth and development respond slowly to greenhouse climate changes. The control horizon t_f selected here is one day. The long-term crop growth and development are taken into account through the final term in equation (5). In the solar greenhouse the use of solar radiation for heating the greenhouse is essential and may fluctuate rapidly. The short-term crop growth is accounted for by the dry weight, which is a function of the photosynthesis rate. Photosynthesis is instantaneously influenced by solar radiation. Therefore a relatively small sampling period of 10 minutes has been selected.

2. Control Inputs. Only the two discretized control inputs (vp_h, Ap_{csd}) are computed by the receding horizon optimal controller. For heating/cooling the combined heating valve position vp_h [-1, 2] is used. It is divided into the valve positions for heat exchanger vp_{he}, heat pump vp_{hp}, lower net vp_l and upper net vp_u

$$vp_{he}(t) = \begin{cases} -vp_h(t) & -1 \le vp_h(t) < 0 \\ 0 & 0 \le vp_h(t) \le 2 \end{cases} \qquad vp_l(t) = \begin{cases} 0 & -1 \le vp_h(t) \le 1 \\ vp_h(t) - 1 & 1 < vp_h(t) \le 2 \end{cases}$$

$$vp_{hp}(t) = \begin{cases} 0 & -1 \le vp_h(t) < 0 \\ vp_h(t) & 0 \le vp_h(t) \le 1 \\ 1 & 1 < vp_h(t) \le 2 \end{cases} \qquad vp_u(t) = \begin{cases} 0 & -1 < vp_h(t) \le 1 \\ vp_h(t) - 1 & 1 < vp_h(t) \le 2 \end{cases}$$

For ventilation the combined window aperture Ap_{csd} [0, 2] is used. It is divided into the lee-side Ap_{lsd} and windward-side Ap_{wsd} window aperture

$$Ap_{lsd}(t) = \begin{cases} Ap_{csd}(t) & Ap_{csd}(t) \le 1 \\ 1 & Ap_{csd}(t) > 1 \end{cases} \qquad Ap_{wsd}(t) = \begin{cases} 0 & Ap_{csd}(t) \le 1 \\ Ap_{csd}(t) - 1 & Ap_{csd}(t) > 1 \end{cases}$$

The valve position CO_2 supply vp_{CO2} is controlled with a proportional controller. The CO_2 set point $C_{a\_CO2\_sp}$ [ppm] is determined directly based on the combined window aperture Ap_{csd} and the incoming short-wave radiation I_o

$$C_{a\_CO2\_sp}(t) = \begin{cases} C_{a\_CO2\max} - \dfrac{Ap_{csd}}{4} \cdot \left(C_{a\_CO2\max} - C_{a\_CO2\min} \right) & I_o > 0 \\ 0 & I_o = 0 \end{cases}$$

$$vp_{CO2}(t) = 0.01 \cdot \left(C_{a\_CO2\_sp}(t) - C_{a\_CO2a}(t) \right)$$

This valve position is constrained to the range [0, 1].

Ventilation with heat recovery op_{vhr} is used at times of heat demand, which is determined by the use of heat pump or boiler ($vp_h > 0$). When ventilation with heat recovery is used, 90% of the sensible heat is recovered. Its value is 0 (false) or 1 (true).

The thermal screen closure Ap_{sc} is determined based on the temperature outdoor air T_o and the incoming short-wave radiation I_o. Its value is 0 (open) or 1 (closed).

3. Temperature Integral. For the temperature integral a time period of six days is used. The reference temperature T_{aref} is 19°C, with boundary values of ±6°C (see table 1). The temperature integral S_{T_past} is calculated over the past five days, which gives the initial state of the temperature integral. Then the model is simulated during the next day, which gives the temperature integral S_{T_fore}. This gives the temperature integral S_T and the average temperature deviation ΔT_{a_TI} over six days

$$S_T(t) = \underbrace{t_s \cdot \frac{1}{n_{\text{secs}}} \cdot \sum_{t-5 \cdot n_{\text{secs}}}^{t} \left(T_a(\nu) - T_{aref}\right)}_{S_{T\_past}} + \underbrace{\frac{1}{n_{\text{secs}}} \cdot \int_{t}^{t+1 \cdot n_{\text{secs}}} \left(\hat{T}_a(\nu) - T_{aref}\right) d\nu}_{S_{T\_fore}} \quad \text{[K·day]}$$

$$\Delta T_{a\_TI}(t) = \frac{S_T(t)}{5 + \frac{t}{n_{\text{secs}}}} \quad \text{[K]}$$

with time t (s), n_{secs} is the number of seconds per day and $S_{T\_past}(t - 5 \cdot n_{\text{secs}}) = 0$. The latter means that temperature deviations of more than five days ago are not taken into account. The temperature integral is used in the cost function to keep the average temperature deviation ΔT_{a_TI} within the boundary values of ±6°C and to obtain an average temperature deviation of zero at the end of the control horizon of one day.

RESULTS AND DISCUSSION

The optimal control inputs and results are given per season in figures 1 and 2. The leftmost figures show window aperture (lee- Ap_{lsd} and windward-side Ap_{wsd}), thermal screen closure Ap_{sc}, and valve positions for CO_2 supply vp_{CO2}, lower net vp_l, upper net vp_u, heat pump vp_{hp} and heat exchanger vp_{he}. When ventilation with heat recovery is used, the window aperture is given as a dashed line. The rightmost figures show the terms that determine the costs. These include temperature T_a (°C), relative humidity RH_a (%), CO_2 concentration (kg·m^{-3}) of the indoor air below the screen, energy used and recovered Q_{sum} (W·m^{-2}), crop dry weight increase ΔW_f (kg·m^{-2}), average temperature deviation over six days ΔT_{a_TI} (°C) and resulting cost function value J.

Spring and Summer

In spring and summer (Fig. 1), the heat pump (vp_{hp}) is used to increase temperature and reduce humidity. The boiler (vp_l, vp_u) is hardly used. The thermal screen (Ap_{sc}) is used less after the first half of April, since outdoor temperature and radiation increase. The heat exchanger (vp_{he}) is used to decrease temperature. Ventilation with heat recovery (op_{vhr}) is used to reduce humidity at times of heat surplus. Normal ventilation is rarely used. The CO_2 supply (vp_{CO2}) is fully opened most of the time. This results in a large crop dry weight increase ΔW_f. This growth implies a high photosynthesis rate and therewith a high use of CO_2, resulting in a low CO_2 concentration C_{a_CO2}.

Temperature T_a varies from 10.2°C (night time) to 36.2°C (day time). At times of high radiation, temperature is allowed to rise, since this yields a higher dry weight increase. The average temperatures are 18.95°C (spring) and 19.09°C (summer), which are close to the reference temperature T_{aref} of 19°C. Relative humidity RH_a ranges from 24.3% to 98.5%. At high relative humidity, ventilation, heat pump and even the boiler are used to decrease it. At the start of June, the average temperature deviation rises up to 1.5°C, while the heat exchanger is on and the windows are opened to cool the greenhouse.

Fall and Winter

In fall and winter (Fig. 2), the heat pump (vp_{hp}) is used to increase temperature and reduce humidity. The boiler (vp_l, vp_u) is used to supply additional heat to the greenhouse, since the capacity of the heat pump is limited. The thermal screen (Ap_{sc}) is used almost every night, and sometimes stays closed during daytime if radiation and temperature are low. The heat exchanger (vp_{he}) is seldom used. Ventilation with heat recovery (op_{vhr}) is used to reduce humidity at times of heat surplus. Normal ventilation is not used. The CO_2 supply (vp_{CO2}) is fully opened most of the time. This results in a lower crop dry weight increase ΔW_f compared to spring and summer, since there is less radiation.

Temperature T_a varies from 13.5°C (night time) to 32.6°C (day time). At times of high radiation, temperature is allowed to rise, since this yields a higher dry weight increase. The average temperatures are 18.89°C (fall) and 18.85°C (winter), which are very close to the reference temperature T_{aref} of 19°C. Relative humidity RH_a ranges from 37.3% to 99.6%. At high relative humidity, ventilation, heat pump and the boiler are used to decrease it.

General Remarks

The thermal screen (Ap_{sc}) is closed depending on outside temperature and radiation. This can lead to screen closure during the day in fall and winter. In the second half of spring and in summer, the screen rarely closes. The windows (Ap_{lsd}, Ap_{wsd}) are mainly opened to decrease humidity, since temperature can be decreased with the heat exchanger. In summer they are used to decrease temperature. The heat pump (vp_{hp}) is used year-round, either to increase temperature or to decrease humidity. The boiler (vp_l, vp_u) is used to further increase temperature or to further decrease humidity in fall and winter. The heat exchanger (vp_{he}) is used in spring and summer to decrease temperature. CO_2 supply (vp_{CO2}) is used whenever there is radiation. When the windows are opened, the CO_2 supply is decreased. In the second half of spring and in summer, the uptake by the crop of CO_2 leads to low CO_2 concentrations in the greenhouse.

Temperature T_a remains within its bounds relatively well, exceeding the upper bound of 34°C sometimes during daytime in spring and summer. Relative humidity RH_a exceeds its bound quite often, while the optimal control is doing everything it can (heating, ventilating) to decrease it. The highest dry weight increase ΔW_f is found in spring and summer, which is obviously due to higher radiation in these seasons. The average temperature ΔT_{a_TI} over six days never reaches its bounds of ±6°C. It has a maximum value of 1.5°C. The reference temperature of 19°C is well met in all seasons.

Optimal Control without Solar Greenhouse Elements

If the solar greenhouse elements (heat pump, heat exchanger, ventilation with heat recovery) are removed from the greenhouse model, the model describes a conventional greenhouse. The optimal control is tested on this conventional greenhouse for comparison with the solar greenhouse.

The trajectories of T_a, RH_a and C_{a_CO2} (not shown) are comparable to those shown in figures 1 and 2 with solar greenhouse elements. The reference temperature T_{aref} is however not met in fall (18.19°C) and winter (17.03°C). In table 2 the amount of gas used Φ_{gas} and the dry weight increase ΔW_f are given for the solar and the conventional greenhouse. From the results it can be seen that the gas use in the conventional greenhouse is much higher (77%) while the crop dry weight increase is equal to the solar greenhouse. The latter is the result of the CO_2 supply, which is assumed to be independent of boiler operation. If the CO_2 supply depends on boiler operation, the gas use is 24% higher and the crop dry weight is 10% lower, since the amount of CO_2 supplied is lower.

CONCLUSIONS

The receding horizon optimal control has been tested with year-round weather data. From the results, it can be concluded that

- Receding horizon optimal control of the solar greenhouse is feasible. Although the model is non-linear and complex, rational optimal control solutions can be found.
- The heat pump and the heat exchanger are valuable additions to the greenhouse control

system. The greenhouse is heated with the heat pump year-round, while in fall and winter the boiler is needed to supply additional heat. The heat exchanger is used to cool the greenhouse in spring and summer, thus harvesting energy for the aquifer.

- Temperature stays well within bounds, and the temperature integral requirements are well met. Relative humidity exceeds its bound; while the optimal control is doing everything it can (heating, ventilating) to decrease it.
- The use of the solar greenhouse elements (heat pump, heat exchanger and ventilation with heat recovery) results in lower energy costs compared to a conventional greenhouse. The use of CO_2 supply independent of boiler operation results in a higher dry weight increase, since more CO_2 is supplied.

This paper demonstrated the feasibility of receding horizon optimal solar greenhouse climate control. As opposed to the simulations in this paper, the real control of the solar greenhouse can be performed using conventional optimal control algorithms since these generally terminate within the sampling period of 10 minutes. The use of conventional control algorithms is expected to further improve the results, because the control values are no longer constrained to discretized control input values. Implementing such a receding horizon controller and investigating its performance are future research topics.

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Tables

Table 1. Cost function: cost and penalties.

symbol	unit	x_{min}	x_{max}	cost·day^{-1}·unit^{-1}	
T_a	[°C]	10	34	c_T	= 5
ΔT_{a_TI}	[°C]	-6	6	c_{TI}	= 25
T_{aref}	[°C]	19			
RH_a	[%]	–	85	c_{RH}	= 5
C_{a_CO2}	[ppm]	320	1000	c_{CO2}	= 0
Q_{sum}	[W·m^{-2}]			c_Q	= 0.1677
W_f	[kg·m^{-2}]			c_{Wf}	= 76.8

Table 2. Results gas use and dry weight increase.

symbol	unit		spring	summer	fall	winter	year
Φ_{gas}	[m^3·m^{-2}·season^{-1}]	solar	1.43	1.26	8.42	12.21	23.32
		conv.	3.27	5.91	15.51	16.67	41.36
ΔW_f	[kg·m^{-2}·season^{-1}]	solar	17.64	15.12	3.55	2.75	39.06
		conv.	17.21	15.56	3.57	2.74	39.08

Figures

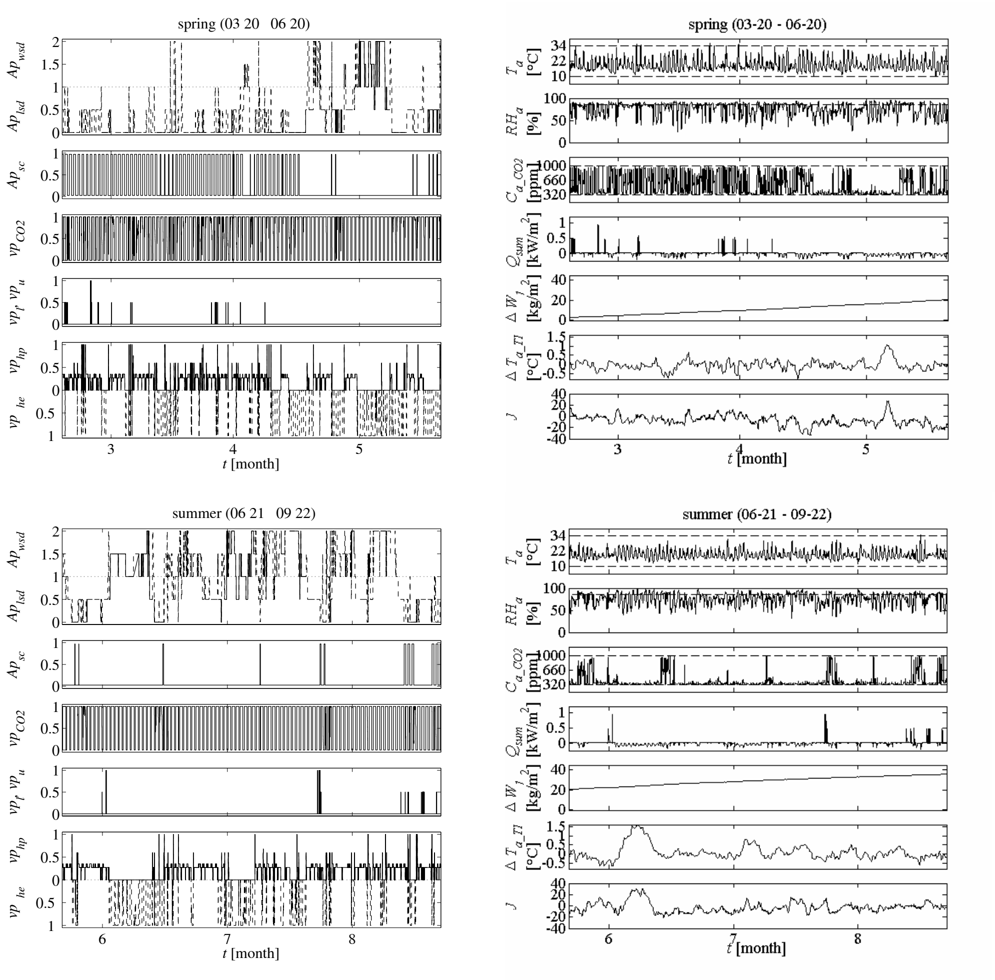

Fig. 1. Optimal control inputs and results spring and summer.

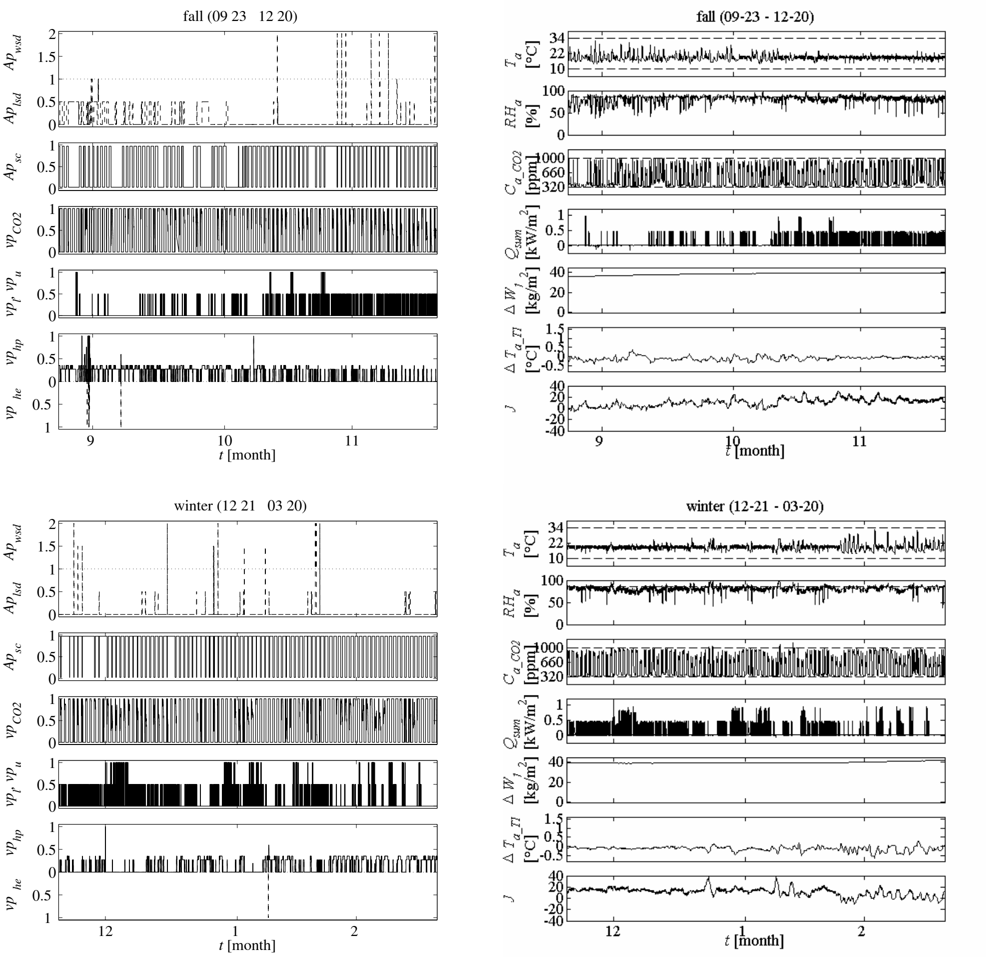

Fig. 2. Optimal control inputs and results fall and winter.