OPTIMAL CONTROL OF A SOLAR GREENHOUSE

R.J.C. van Ooteghem, J.D. Stigter, L.G. van Willigenburg, G. van Straten

Systems and Control Group, Department of Agrotechnology and Food Science,
Wageningen University, Mansholtlaan 10, 6708 PA, Wageningen, The Netherlands
E-mail: Rachel.vanOoteghem@wur.nl

A solar greenhouse has been designed that maximizes solar energy use and minimizes fossil energy consumption. It is based on a conventional greenhouse extended with a heat pump, a heat exchanger, an aquifer and ventilation with heat recovery. The aim is to minimize fossil energy consumption, while maximizing crop dry weight and keeping temperature and humidity within certain limits. These requirements are defined in a goal function, which is minimized by optimal control. A greenhouse with crop model is used to simulate the process behaviour. It is found that open loop optimal control trajectories can be determined. The boiler use is reduced to a minimum, thus reducing fossil energy use. Compared to a conventional greenhouse it is found that the energy costs are decreased and the crop dry weight is increased.

Keywords: optimal control; dynamic model; energy management; gradient method; model based control

1. INTRODUCTION

Greenhouse horticulture is an important branch of industry for Dutch economy. The intensive crop production however involves high input of fossil energy. The consumption of natural gas in greenhouse horticulture is now about 12.5% of the total national consumption. A new greenhouse is designed 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.

1.1 Solar greenhouse design

In the greenhouse design the heat insulation and the transmission of solar radiation are maximized. An aquifer is used to store the solar energy. The aquifer consists of a warm- and a cold-water basin in soil. At times of heat demand, the greenhouse can be heated with little energy input 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. The CO_2 supply is independent of boiler operation, thus avoiding the need to use the boiler at times of CO_2 demand. Ventilation with heat recovery is added to dehumidify the greenhouse at times of heat demand.

1.2 Optimal control

The solar greenhouse design with extra control possibilities is a challenge from the control-engineering point of view. Optimal control has been used to control the greenhouse climate in conventional greenhouses by Van Henten (1994) and Tap (2000). Van Henten concluded that using optimal control could give a significant improvement in efficiency of greenhouse climate management in theory. The performance of the optimal control largely depends on the ability of the control system to deal with modelling and weather prediction errors. Tap showed that only short-term weather predictions are needed for optimal greenhouse climate control. They both state that good results can be obtained with optimal control. An indirect gradient method (Bryson, 1999) is used to calculate the optimal control trajectories. This method has proven its effectiveness in conventional greenhouse control and many other fields (Van Willigenburg, 2000).

1.3 Solar greenhouse model

For application of optimal control an accurate model of the controlled processes is necessary. Van Henten (1994) and Tap (2000) found that parts of the greenhouse behaviour were not well described by their models. This affects the performance of the optimal control. The model should be as small as possible with respect to the number of differential equations, controls and disturbances for good insight and fast calculation. It should also give a good description of the dynamic variables as a function of the applied controls and disturbances. The dynamic model used in this research consists of models of greenhouse climate (Heesen, 1997), crop photosynthesis (Farquhar, 1980) and crop evaporation (Stanghellini, 1987). The model has been validated with greenhouse data, and was found to give an accurate description of the processes. The model has been extended with the new solar greenhouse elements (heat pump, heat exchanger, ventilation with heat recovery). The main disturbance is the weather, which can be forecasted quite accurately for one or two days ahead.

The calculation of control trajectories for the new heating system of the solar greenhouse will give a better insight of the profit of the solar greenhouse design.

2. MATERIALS AND METHODS

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

2.1 Greenhouse and crop model

The greenhouse model used in this research has been developed by Heesen (1997) based on the research by Van Henten (1994), De Zwart (1996), De Jong (1990) and Bot (1983). A photosynthesis model (Farquhar, 1980) and an evaporation model (Stanghellini, 1987) are used to simulate the crop responses. This model (Van Ooteghem, 2003) is used for all calculations in this paper.

The greenhouse model is written in state space form

$$\dot{x} = f(t, x, u, v)$$

where t is time, x are states, u are control inputs, v are external inputs (disturbances) and f is a non-linear function. The contents of these variables are given in table 1.

The state equations have been formed based on the laws of conservation of enthalpy and matter. The dynamic behaviour of the states is described using first order differential equations.

Table 1: States, control inputs and disturbances

	symbol	description
states	T_r	temperature indoor roof [K]
	T_a	temperature indoor air [K]
	T_c	temperature crop [K]
	T_s	temperature soil (upper layer) [K]
	T_l	temperature lower net [K]
	T_u	temperature upper net [K]
	C_{a_CO2}	CO_2 concentration indoor air [kg·m^{-3}]
	C_{a_H2O}	H_2O concentration indoor air [kg·m^{-3}]
	W_f	crop dry weight [kg·m^{-2}]
control inputs	Ap_{lsd}	window aperture lee-side [0..1]
	Ap_{wsd}	window aperture windward-side [0..1]
	op_{vhr}	option ventilation heat recovery [0/1]
	vp_{CO2}	valve position CO_2 supply [0..1]
	vp_l	valve position lower net [0..1]
	vp_u	valve position upper net [0..1]
	vp_{he}	valve position heat exchanger [0..1]
	vp_{hp}	valve position heat pump [0..1]
disturbances	I_o	incoming shortwave radiation [W·m^{-2}]
	v_o	wind speed outdoor [m·s^{-1}]
	T_o	temperature outdoor [K]
	T_{sk}	temperature sky [K]
	T_{o_n}	temperature wet bulb [K]
	C_{o_CO2}	CO_2 concentration outdoor [kg·m^{-3}]

Greenhouse model The greenhouse model is based on a Venlo-type greenhouse with a North-South orientation (Heesen, 1997). The greenhouse has no lighting since this gives energy costs, and no screen since this would interfere with the maximum solar radiation intake. The roof has a double glass cover. The greenhouse has two heating nets: a lower and an upper net, which can be heated with a boiler. The lower net can be heated with a heat pump and cooled by a heat exchanger. The heat pump can only be used at times of low heat demand since it can only heat to about 40°C. It is assumed that the CO_2 supply is independent of the boiler heat supply. Ventilation with heat recovery is applied by preheating the outdoor air with indoor air. For the heat and mass transport the following elements are taken into account: indoor air, crop, heating pipes, roof and soil. These elements are modelled as lumped parameter models, where it is assumed that the compartments are internally homogeneous. Soil and roof are divided into two layers/parts.

Crop model The crop is grown on substrate. The substrate is placed in a gutter, covered with white plastic. It is assumed that water and nutrient supply is well-controlled and not limiting to crop photosynthesis and evaporation. Crop growth is based on the photosynthesis rate: the production of assimilates from CO_2 and water with solar radiation. Assimilates are used for crop growth and maintenance. The photosynthesis rate is determined by solar radiation, temperature, CO_2 concentration, humidity and leaf area index, based on Farquhar (1980). The dark respiration rate is determined by temperature and indicates the assimilate use at night. The crop evaporation is modelled according to the research by Stanghelinni (1987). Evaporation is necessary to cool the crop leaves and to realise the transport of water and nutrients from the roots to the upper crop parts.

Very high or low temperatures can cause irreversible damage to the crop. High CO_2 concentrations in the indoor air can also cause crop damage, but exact values are not known. In practice a concentration of 1000 ppm is used. High humidity increases the risk at infection by mould. The horticulturist can choose the temperature and humidity bounds. For the short-term the temperature and humidity should remain within these bounds. For the long-term these bounds may be crossed, which will be included in the temperature integration at a later stage.

2.2 Optimal control

In optimal control, control input trajectories are determined, based on a goal function. The control solution consists of actuator trajectories, which result in temperature, humidity and CO_2 concentration that optimise a goal function. The aim is to minimize fossil energy consumption, while maximizing crop dry weight and keeping temperature and relative humidity within certain limits. In the goal function costs are defined to penalize fossil energy consumption and to keep temperature and humidity within bounds. The dry weight increment during the control horizon is defined as a negative final cost.

Given a dynamic system whose evolution in time is described by a set of ordinary differential equations

$$\dot{x} = f(t, x, u, v) \quad (1)$$

where t is time, $x = x(t) \in \Re^n$ is the state vector, $u = u(t) \in \Re^m$ is the control input vector, $v = v(t) \in \Re^w$ is the external input vector and f is a non-linear function.

The goal is to minimize the cost function

$$J(u) = -\Phi(x,t) + \int_{t_0}^{t_f} L(x,u,t)dt \quad (2)$$

where $\Phi : \Re^{n+1} \rightarrow \Re$ and $L : \Re^{n+m+w+1} \rightarrow \Re$ are differentiable a sufficient number of times with respect to their arguments. The final time t_f is set to the prediction horizon, which is equal to one or two days, and therefore will not be subject to optimisation.

The control inputs are constrained by

$$u_{i,\min} \le u_i(t) \le u_{i,\max} \qquad i = 1, \ldots, m \quad (3)$$

A control vector $u(t)$ that satisfies the constraints (3) is called admissible. For the states there are trajectory constraints, which are considered “soft”. With these prerequisites the control problem is to find

$$u^*(t) = \arg\min_u J(u) \quad (4)$$

given a prediction of $v(t)$ for $t \in [t_0, t_f]$, subject to the differential equations (1) and the control constraints (3). In other words, the objective is to find admissible input trajectories $u^*(t)$ on the time interval $t \in [t_0, t_f]$ such that the process given by (1) has states trajectories that minimize the performance criterion J. The resulting control and state trajectories are referred to as the optimal trajectories.

The function L [cost·s^{-1}] is given by the sum of the penalties for temperature T_a, relative humidity RH_a and energy consumption Q

$$L(x,u,t) = L_{Ta}(x,u,t) + L_{RHa}(x,u,t) + L_Q(x,u,t) \quad (5)$$

Since the penalty function L has to be integrated in time, the Mayer formulation (Bryson, 1999) is used, which extends the state vector with an extra state L.

The penalties for temperature and relative humidity are given by

$$L_x(x,u,t) = \begin{cases} c_x \cdot (x(t) - x_{\min}) & x(t) < x_{\min} \\ 0 & x_{\min} \le x(t) \le x_{\max} \\ c_x \cdot (x_{\max} - x(t)) & x(t) > x_{\max} \end{cases} \quad (6)$$

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

$$\begin{aligned} L_Q(x,u,t) &= c_Q \cdot (Q_{boil} + Q_{hp} - \eta \cdot Q_{he}) \\ &= c_Q \cdot Q_{sum} \end{aligned} \quad (7)$$

where Q_{sum} [W·m^{-2}] denotes energy used by boiler and heat pump and recovered by the heat exchanger. An efficiency factor $\eta = 0.5$ is introduced for the heat exchanger, since only a part of the recovered energy can be reused.

The final cost Φ are determined by the yield in the form of crop dry weight W_f

$$\Phi(x,t) = c_{Wf} \cdot (t_f - t_0) \cdot (W_f(t_f) - W_f(t_0)) \quad (8)$$

In table 2 the values used in the cost function are given.

Table 2: Cost function: cost and penalties

symbol	unit	$x_{\min}$	$x_{\max}$	cost·day^{-1}·unit^{-1}
T_a	[°C]	16	24	$c_T = 5$
RH_a	[%]	–	85	$c_{RH} = 2$
CO_{2a}	[ppm]	320	1000	$c_{CO2} = 0$
Q_{sum}	[W·m^{-2}]			$c_Q = 0.1677$
W_f	[kg·m^{-2}]			$c_{Wf} = 76.8$

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 minimization of the cost function J can be performed with many different minimization methods. In this research an indirect gradient method (Bryson, 1999) is used to calculate the optimal control trajectories.

Control horizon and time interval The control horizon is determined by the computation time, the time interval for the control inputs and the weather forecast time span. Time intervals ranging from one hour to several days are used in research by Shina and Seginer (1989) and Van Henten and Bontsema (1991). These long time intervals are used because crop growth and development respond slowly to greenhouse climate changes. In the solar greenhouse the use of solar radiation for heating the greenhouse is essential, which calls for a time interval smaller than one hour. A smaller time interval will result in a longer computation time; therefore the control horizon is limited to a maximum of two days. The short-term crop growth is accounted for by dry weight, which is a function of photosynthesis rate. Photosynthesis rate is affected by solar radiation, temperature, humidity and CO_2 concentration. To include long-term crop growth and development, temperature integration will be introduced in the goal function over a range of three to six days. In this paper the use of open loop optimal control on a solar greenhouse including the heat pump, heat exchanger, separate CO_2 supply and ventilation with heat recovery is described. The temperature integration will be included in the optimal control at a later stage. In this paper the control horizon is one day, the time interval for the control inputs is half an hour and the maximum integration time step is 1 minute. This means that 48 values are determined by the optimal control for each control input.

Control inputs In conventional greenhouse control, the greenhouse climate is controlled by heuristic rules and setpoints. The optimal control algorithm uses a simulation of the greenhouse climate with varying control input values along the control horizon to calculate the goal function value. The greenhouse climate can be modelled with different control inputs. In conventional control of the greenhouse temperature, setpoints are defined for the heating and ventilation temperature. If these setpoints are used as control inputs for the optimal control, an internal (heuristic) control has to be included to calculate the desired heat flow or heating valve position. The incorporation of the heuristic control rules in the optimal control decreases the optimal control freedom. Therefore the greenhouse climate model used in this research is based on actuator values as control inputs.

Only two optimal control inputs are used in the optimisation. For ventilation the combined window aperture Ap_{csd} [0..2] is used. It is split into the lee-side Ap_{lsd} and windward-side Ap_{wsd} window aperture

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

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

For heating/cooling the combined heating valve position vp_h [-1..2] is used. It is split into the valve positions for heat exchanger vp_{he}, heat pump vp_{hp}, lower net vp_l and upper net vp_u

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

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

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

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

State dependent control input bounds Based on a priori knowledge of the system, the following bounds are set on the control inputs to push the optimal control solutions into the correct direction.

The bounds are based on the simulated values of the initial states of the control interval (half an hour). From the states, the values of temperature indoor air T_a and relative humidity indoor air RH_a (based on H_2O concentration indoor air C_{a_H2O}) are used to determine the input bounds. The maximum and minimum values for T_a and RH_a are equal to the boundary values given in table 2.

Control input bound on combined window aperture Ap_{csd} [0..2]

$$Ap_{csd\,\max}(t) = 1 \quad T_a < T_{a\max} \text{ and } RH_a < RH_{a\max}$$

This can be interpreted as:

- Less ventilation if temperature T_a and relative humidity RH_a are below their upper bounds.

Control input bounds on combined heating valve position vp_h [-1..2]

$$vp_{h\max}(t) = 1 \quad T_{a\min} < T_a < T_{a\max}$$
$$vp_{h\max}(t) = 0 \quad T_{a\max} < T_a$$
$$vp_{h\min}(t) = 0 \quad T_a < T_{a\min}$$

This can be interpreted as:

- No heating with the boiler if temperature T_a is above its lower bound $T_{a\min}$.
- No heating with the heat pump if temperature T_a is above its upper bound $T_{a\max}$.
- No cooling with the heat exchanger if temperature T_a is below its lower bound $T_{a\min}$.

The valve position CO_2 supply vp_{CO2} is controlled with a proportional controller. The CO_2 setpoint $CO_{2a\text{-sp}}$ [ppm] is determined based on the combined window aperture Ap_{csd} and the incoming shortwave radiation I_o

$$CO_{2a\text{-}sp}(t) = \begin{cases} CO_{2a\max} - \dfrac{Ap_{csd}}{4} \cdot \left(CO_{2a\max} - CO_{2a\min}\right) & I_o > 0 \\ 0 & I_o = 0 \end{cases}$$

$$vp_{CO2}(t) = 0.01 \cdot \left(CO_{2a\text{-}sp}(t) - CO_{2a}(t)\right) \qquad (9)$$

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

If ventilation with heat recovery is used, 70% of the sensible heat is recovered. This is used at times of heat demand, which is determined by the use of heat pump or boiler ($vp_{hp} > 0$ or $vp_l > 0$).

Calculation The open loop optimal control trajectories are calculated over the course of one day. Measured weather data is averaged to obtain one-hourly weather data. The results for two days are evaluated, one in summer and one in winter.

The optimal control calculation is started with constant initial values for both control input trajectories (Ap_{csd}, vp_h). Different initial values yield different optimal control trajectories and different values for the cost function J. To find a good minimum cost function a number of constant initial values are tested, and the best combination is used as initial value for the minimisation.

3. RESULTS AND DISCUSSION

3.1 Weather data

To test the optimal control, two different days are selected, one in summer (1998–7–11), and one in winter (1998–12–29).

On the summer day temperature is between 14 and 19°C; wind speed is between 0.6 and 4 m·s^{-1}; relative humidity is between 48 and 94%; CO_2 concentration is between 290 and 315 ppm and sky temperature is between -4 and 6°C. The incoming shortwave radiation is given in figure 1.

On the winter day temperature is between 2 and 6°C; wind speed is between 0.4 and 3 m·s^{-1}; relative humidity is between 78 and 98%; CO_2 concentration is between 322 and 335 ppm and sky temperature is between -25 and -13°C. The incoming shortwave radiation is given in figure 1.

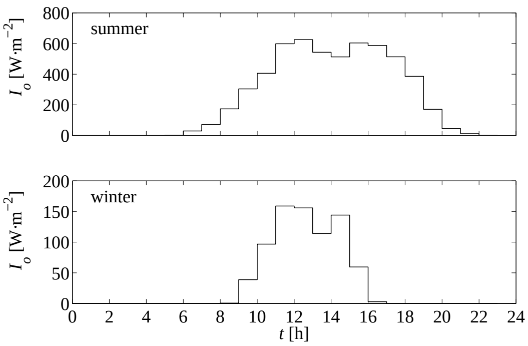

Fig. 1 Solar radiation summer and winter day

3.2 Initial values control inputs

The initial values of the control inputs are set to trajectories with a constant value. The chosen values influence the optimal control solution found, since there is more than one minimum for the goal function J. The best combination of constant initial values for the control inputs is determined by calculating the cost for a number of input combinations. In figures 2 and 3 the resulting cost functions are given for the summer and the winter weather data.

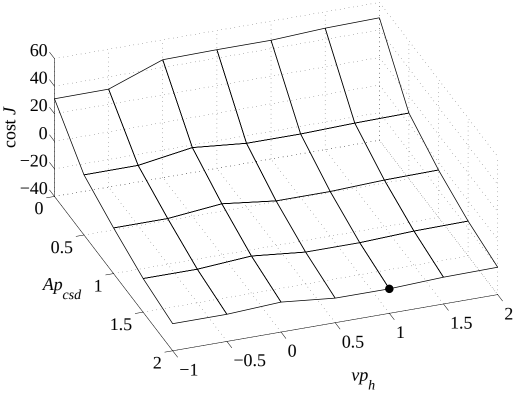

Fig. 2 Cost function in summer (grid of 5*7 values)

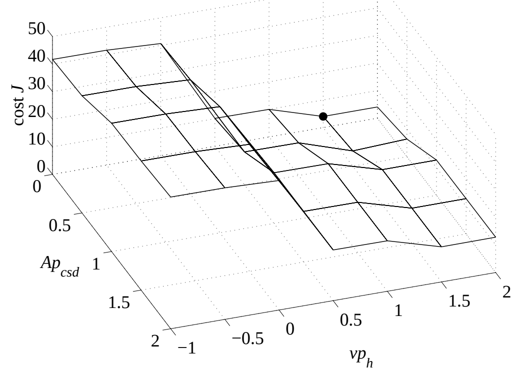

Fig. 3 Cost function in winter (grid of 5*7 values)

From figures 2 and 3 it can be seen that the best initial values for the inputs are not the same for summer and winter. Based on a grid of 5*7 values the best input-combination was determined to calculate the optimal control trajectories. The best input-combinations found are denoted with a dot (●)

$$\text{summer}: \ Ap_{csd} = 2.0 \text{ and } vp_h = 1.0$$
$$\text{winter}: \ Ap_{csd} = 0.0 \text{ and } vp_h = 1.5$$

3.3 Optimal control summer day

In the optimal control trajectories of the summer day the boiler is not used. The window aperture and valve positions of the CO_2 supply, upper and lower net, heat pump and heat exchanger are given in figure 4. The dashed lines for the window aperture indicate ventilation with heat recovery. In figure 5 the optimal state trajectories are given.

The accompanying costs J are determined by the integrals of the penalties L and the final costs Φ:

$$J(u) = -27.66 \qquad \Phi\left(W_f(t_f), t_f\right) = 30.47$$

$$\int_{t_0}^{t_f} L_{Ta}dt = 4.22; \quad \int_{t_0}^{t_f} L_{RHa}dt = 1.30; \quad \int_{t_0}^{t_f} L_Q dt = \text{-}2.71$$

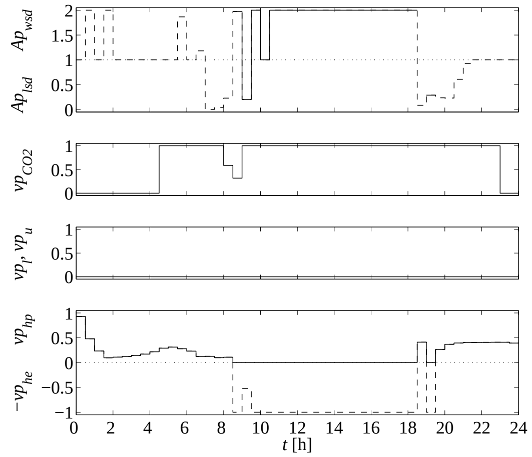

Fig. 4 Optimal control input trajectories summer

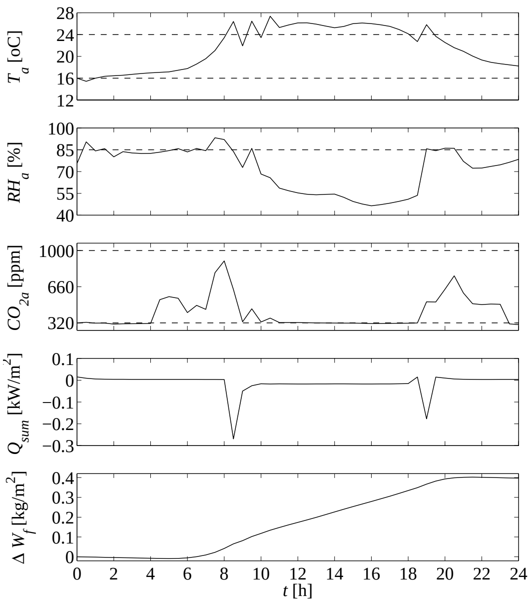

Fig. 5 Optimal state trajectories summer with bounds (dashed)

While there is sunlight, the CO_2 supply vp_{CO2} is fully opened most of the time. With high solar radiation this results in a large increase of the dry weight W_f. This growth implies a high photosynthesis rate and therewith a high use of CO_2, resulting in a low CO_2 concentration CO_{2a}.

While the temperature T_a is within its bounds, the heat pump valve vp_{hp} is opened to increase temperature. The temperature increase causes a decrease in relative humidity RH_a, keeping the latter below its bound. It also causes a higher photosynthesis rate, increasing dry weight W_f.

The heat exchanger valve vp_{he} is opened between the hours 8 and 20 to decrease the temperature T_a, keeping it almost within its bounds.

3.4 *Optimal control winter day*

In the optimal control trajectories of the winter day the heat exchanger is not used. The window opening is small. The greenhouse is mainly heated with the heat pump during daytime. The boiler is used if the heat demand is higher during nighttime. The window aperture and valve positions of the CO_2 supply, upper and lower net, heat pump and heat exchanger are given in figure 6. The dashed lines for the window aperture indicate ventilation with heat recovery. In figure 7 the optimal state trajectories are given.

The accompanying costs J are determined by the integrals of the penalties L and the final costs Φ:

$$J(u) = -0.06 \qquad \Phi\left(W_f(t_f), t_f\right) = 14.07$$

$$\int_{t_0}^{t_f} L_{Ta}\,dt = 1.18; \quad \int_{t_0}^{t_f} L_{RHa}\,dt = 0.00; \quad \int_{t_0}^{t_f} L_Q\,dt = 12.83$$

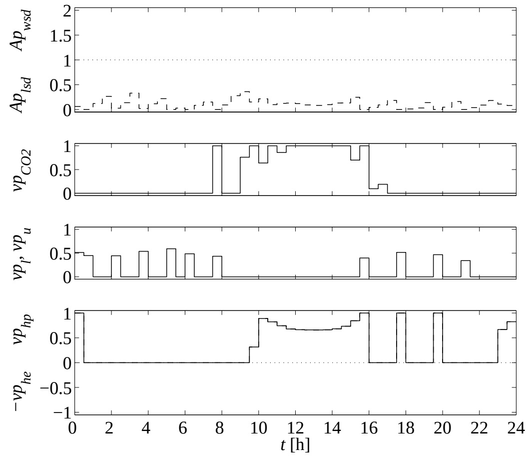

Fig. 6 Optimal control input trajectories winter

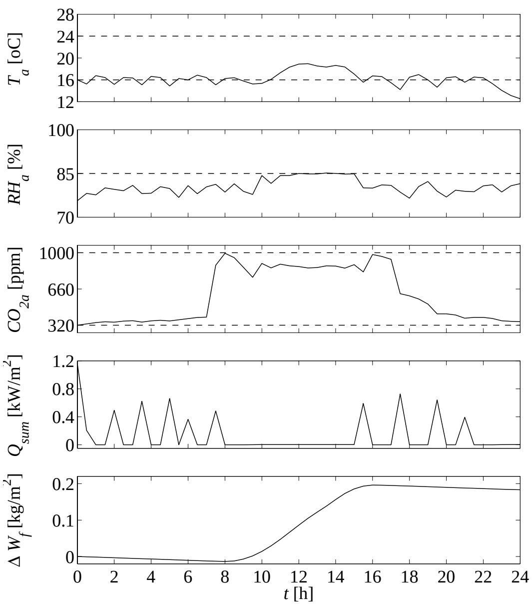

Fig. 7 Optimal state trajectories winter with bounds (dashed)

While there is sunlight, the proportional CO_2 control defined by (9) is used to control the CO_2 supply vp_{CO2}. Most of the time the valve is fully opened, except when the CO_2 concentration is between 900 and 1000 ppm. A small decrease in the CO_2 concentration can be seen between the hours 8 and 17, which correspond to the hours with solar radiation. The photosynthesis rate is lower on the winter day compared to the summer day due to less solar radiation. This causes less CO_2 consumption and a smaller increase of dry weight W_f.

The heat pump valve vp_{hp} is used to increase temperature during daytime, when the heat demand is low. The boiler (vp_l, vp_u) is used at nighttime, when the heat demand is higher, keeping the temperature almost within its bounds. Due to less solar radiation the increase in dry weight W_f that could be achieved by increasing the temperature T_a does not countervail against the cost of heating.

The relative humidity RH_a stays well below its bound. This is due to a lower crop evaporation rate on account of a lower photosynthesis rate and a lower temperature T_a.

3.5 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.

Values costs J, integrals of the penalties L and the final costs Φ in summer without solar greenhouse elements:

$$J(u) = -15.93 \qquad \Phi\big(W_f(t_f), t_f\big) = 24.28$$

$$\int_{t_0}^{t_f} L_{Ta}\,dt = 4.06; \quad \int_{t_0}^{t_f} L_{RHa}\,dt = 1.48; \quad \int_{t_0}^{t_f} L_Q\,dt = 2.81$$

Values costs J, integrals of the penalties L and the final costs Φ in winter without solar greenhouse elements:

$$J(u) = 7.22 \qquad \Phi\big(W_f(t_f), t_f\big) = 13.31$$

$$\int_{t_0}^{t_f} L_{Ta}\,dt = 2.83; \quad \int_{t_0}^{t_f} L_{RHa}\,dt = 0.07; \quad \int_{t_0}^{t_f} L_Q\,dt = 17.63$$

The trajectories of the variables T_a, RH_a and CO_{2a} (not shown) are comparable to those shown in figures 5 and 7 with solar greenhouse elements. In table 3 the total amount of energy used $\sum Q_{sum}$ and the increase of dry weight ΔW_f are shown. From the results it can be seen that the energy use in the conventional greenhouse is higher and the increase in crop dry weight is lower than in the solar greenhouse.

Table 3: Results energy and dry weight

symbol	unit		summer	winter
$\sum Q_{sum}$	$[\mathrm{W \cdot m^2 \cdot day^1}]$	solar	-16.16	76.50
		conv.	16.75	105.12
ΔW_f	$[\mathrm{kg \cdot m^2 \cdot day^1}]$	solar	0.40	0.18
		conv.	0.32	0.17

4. CONCLUSIONS

From the open loop optimal control results found, we can conclude that

- Optimal control of the solar greenhouse is feasible.
- Although the model is non-linear and complex, rational optimal control solutions can be found.
- The control and state trajectories can be interpreted easily, since the internal variables have physical meaning.
- The use of a pre-calculation of the constant initial optimal control values can be used to obtain control trajectories that are more likely to go to a good minimum of the cost function.
- The results of the optimal control strongly depend on the weather conditions; therefore reliable forecasts are needed.
- The boiler, heat pump and heat exchanger are used only if it yields a profit in the optimal control goal function. This causes temperature and relative humidity close to their bounded values.
- The use of the solar greenhouse elements (heat pump, heat exchanger and ventilation with heat recovery) results in lower energy costs and a higher dry weight increase.

In further research, the open loop optimal control will be extended to a receding horizon optimal control to control the greenhouse processes. Tap (2000) and Van Henten (1994) used this on a conventional greenhouse. They both found that optimal control in greenhouse is feasible.

For the receding horizon optimal control, initial state values are needed at each new sampling time to calculate new optimal control trajectories. A state estimation is needed to calculate these initial states. An extended Kalman filter could be introduced to estimate these states.

Adaptive control can be used to improve the model by adapting model parameters that are not or not well known. This can also be included in the extended Kalman filter.

ACKNOWLEDGEMENTS

This research is funded by EET, the Dutch institute for Economy, Ecology and Technology.

REFERENCES

Bot, G.P.A. (1983). *Greenhouse climate: from physical processes to a dynamic model*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Bryson Jr., A.E. (1999). *Dynamic optimization*, Menlo-Park, California: Addison-Wesley.

de Jong, T. (1990). *Natural ventilation of large multi-span greenhouses*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

de Zwart, H.F. (1996). *Analyzing energy-saving options in greenhouse cultivation using a* *simulation model*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Farquhar G.D., S. von Caemmerer and J.A. Berry (1980). A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species, *Planta*, **149**, 78-90.

Heesen, L. (1997). *Definitie, gevoeligheidsanalyse en evaluatie van een dynamisch model van het kas-gewasproductieproces*, M.Sc. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Shina, G. and I. Seginer (1989). Optimal management of tomato growth in greenhouses, *Acta Horticulturae*, **248**, 307-313

Stanghellini, C. (1987). *Transpiration of greenhouse crops – an aid to climate management*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Tap, R.F. (2000). *Economics-based optimal control of greenhouse tomato crop production*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

van Henten, E.J. and J. Bontsema (1991). Optimal control of greenhouse climate, In: *Mathematical and control applications in agriculture and horticulture* (Hashimoto, Y. and W. Day (eds.)), IFAC Workshop Series, **1**, 27-32.

van Henten, E.J. (1994). *Greenhouse climate management: an optimal control approach*, Ph.D. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

van Ooteghem (2003). *The solar greenhouse model; Extension of the greenhouse with crop model*, Internal report, Wageningen University, Wageningen, The Netherlands.

van Willigenburg, E.J. van Henten and W.Th.M. van Meurs (2000). Three time-scale receding horizon optimal control in a greenhouse with a heat storage tank, In: *Proceedings of the Agricontrol 2000 conference*, 12-14 July 2000, Wageningen, The Netherlands.