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Improving the efficiency of greenhouse climate control: an optimal control approach

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Abstract

In this paper a method to improve the efficiency of greenhouse climate control is described. This method is based on the framework of optimal control theory. By exploiting a dynamic model of the greenhouse crop production process, information of the auction price, the operating costs of the climate conditioning equipment and the outdoor climate conditions, the optimal greenhouse climate control scheme balances on a purely objective basis costs against revenues of operating the climate conditioning equipment.

Though optimal control of greenhouse climate has received considerable attention in the literature, until now little evidence supported by experimental work has been reported as to the possible improvement in efficiency which can be realised using this approach during a whole growing period. This paper reports a first exploration of this matter for a lettuce crop. In a greenhouse experiment the behaviour of conventional greenhouse climate control supervised by the grower was measured. Then, in simulation experiments, optimal control strategies were calculated for the same conditions (outdoor climate, auction price, energy price). The results obtained support the conclusion that a considerable improvement in the efficiency of greenhouse climate management is possible. This improvement may well exceed 15%.

Keywords: greenhouse, climate control, optimal control, lettuce

Introduction

In horticultural practice, greenhouse climate control is considered to be an important tool to control crop growth and production both in a quantitative and a qualitative sense. The particular procedure employed to control crop production by means of climate conditioning is schematically depicted in Figure 1. Depending on the current status of the crop, the grower decides on the set-points of the greenhouse climate variables such as air temperature, humidity and carbon dioxide concentration. These set-points are usually not defined as fixed values. Following rules defined by the

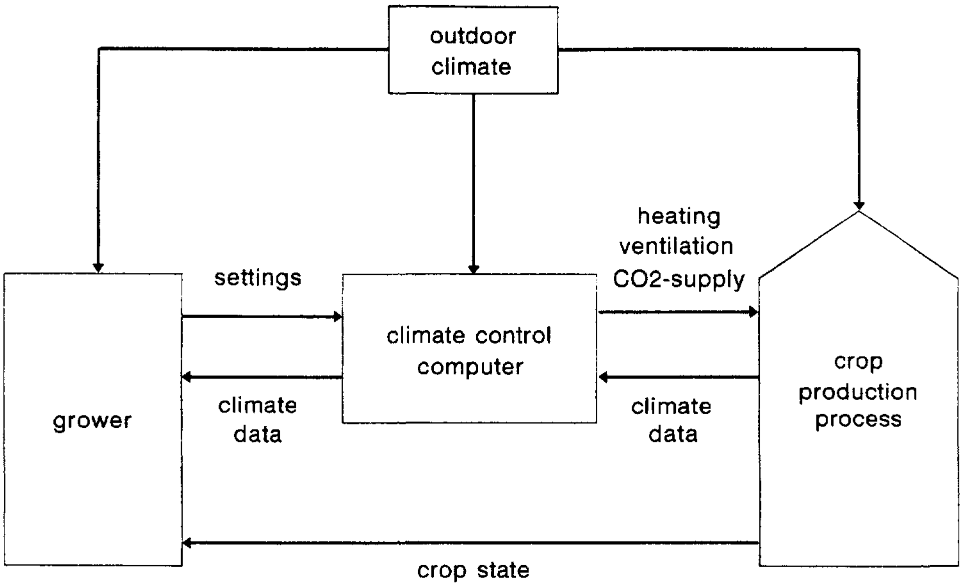

Figure 1. A schematic diagram of the climate control procedure in current horticultural practice.

grower, they may change during actual operation of the climate conditioning equipment in response to changes in the outside climatic conditions. Such adaptations of the set-points include, for example, a solar radiation dependent change of the air temperature set-point, and radiation and ventilation dependent adaptation of the carbon dioxide set-point. The grower may also put bounds on the ventilator's aperture and the temperature of the heating pipes. A minimum temperature of the heating pipes is often used to assure circulation of air within the canopy. All together in modern greenhouse climate control computer systems, a large number of parameters (>150) need to be specified by the grower.

Once the grower has decided on the settings of all these parameters, the greenhouse climate computer aims to achieve the desired climate in the greenhouse using measurements of the indoor climate and feed-back control techniques. There is a second indirect feed-back loop from the crop growth process to the grower, in which during the growing season, the grower may decide to modify the settings on the control computer based on observations of the actual state of the crop and indoor and outdoor climate.

Because the cost of operating modern, sophisticated greenhouses is high, optimal use of their potential is required. Energy consumption, for example, amounts to approximately 15% of total production costs and as such ranks amongst the three most important cost factors for a horticultural firm in The Netherlands. In addition, the consumption of natural gas for horticultural crop production amounts to 10% of the total consumption in The Netherlands. Therefore, any gain in energy efficiency may contribute significantly to an improvement in the economic performance of greenhouse crop production and will be in line with governmental policy aiming at efficient application of natural resources and the reduction of emissions to the environment.

Efficient greenhouse climate management requires a continuous trade-off between the benefits associated with the marketable product against the operating costs of the climate conditioning equipment, taking into account the current state of the process and its future evolution as well as the outdoor climate. At present, in horticultural practice, greenhouse climate control is essentially based on the realisation of climate strategies originating from the grower's experience and from empirical research. Due to the complexity of the physical and physiological processes involved, it is hardly possible for a human operator to achieve energy efficient operation of the greenhouse climate control systems (Challa & Van Straten, 1991). Despite its seemingly advanced appearance, modern greenhouse climate control systems with the large number of parameters to be defined, do not constitute a powerful and simple tool for this purpose. Alternative approaches to greenhouse climate control are needed to obtain the required efficiency.

Climate control based on explicitly balancing economic costs and benefits is a typical example of an optimal control problem (see e.g. Kirk, 1970). Optimal control theory emerged as a new field in academic research in the late 50's and early 60's (Bellman, 1957; Pontryagin *et al.*, 1962). The benefits of optimal greenhouse climate management were discussed in the agricultural engineering literature two decades ago (Udink Ten Cate *et al.*, 1978). However, practical application of optimal control theory has been hampered by the requirement to have an appropriate model of the process to be controlled as well as sufficient computing power. The recent advances in modelling the dynamic responses of crop growth (Sweeney *et al.*, 1981; Goudriaan *et al.*, 1985; Goudriaan & Monteith, 1990), and greenhouse climate (Bot, 1983; Udink Ten Cate, 1983) coupled with the gradual decrease in the price-performance ratio of digital computers during the last decade, renewed the interest in optimal greenhouse climate management (Challa *et al.*, 1988).

Although greenhouse climate management based on the optimal control approach has received considerable attention in the literature (e.g. Seginer *et al.*, 1986; Schmidt *et al.*, 1987; Critten, 1991; Seginer, 1991; Van Henten & Bontsema, 1991; Tap *et al.*, 1993; Van Henten, 1994b; Bailey & Chalabi, 1994; Van Meurs & Van Henten, 1994), not much experimental evidence has yet been reported to support the possible improvement in economics and energy efficiency using this approach for a whole growing season.

The objective of this paper is to analyse the performance of the optimal control approach by comparing the observed behaviour of conventional greenhouse climate control supervised by the grower during an experiment in a real greenhouse, with simulations of the optimal control strategies calculated for the same conditions (outdoor climate, auction price, energy price). This case study focuses on the cultivation of a lettuce crop.

The paper is organised as follows. First, the optimal greenhouse climate control problem is defined. Secondly, the methodology and results of the comparison of optimal greenhouse climate control with conventional greenhouse climate control supervised by the grower are described. Finally, these results are analysed and implications for future research on optimal greenhouse climate control are addressed.

Materials and methods

Formulation of the optimal control problem

The process model

To apply optimal control theory in horticultural practice it is necessary to have a dynamic model describing the evolution of the state variables of the greenhouse crop production process as affected by the state of the process itself, and as influenced by the control and external inputs. In a formal way, the model is represented by

$$\frac{dx}{dt} = f(x,u,v,c,t), \quad x(t_b) = x_b, \tag{1}$$

in which x are the state variables, u are the control inputs, v are the external inputs, c are the model parameters, t denotes time and dx/dt represents the rate of change of the state in time. The initial state of the crop production process is denoted by $x(t_b)$ in which t_b represents the planting date.

Figure 2 shows a schematic diagram of the greenhouse crop production process considered in this research. Although from an economic point of view, lettuce is not considered as one of the important crops in Dutch horticultural practice, it has been used in this research to illustrate the principle of the optimal control approach. It is a single harvest crop which, from the point of view of modelling and optimal control, is much easier to deal with than multiple harvests crops like tomatoes and cucumber. However, the optimal control methodology is equally applicable to the latter type of crops.

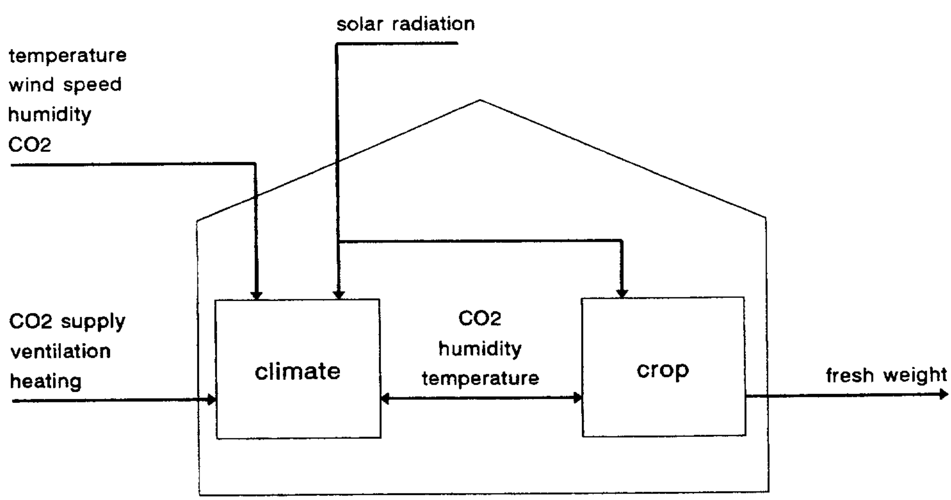

Figure 2. A schematic diagram of the greenhouse crop production process.

The state of the production process is represented by variables relating to the lettuce crop such as crop fresh weight, as well as to variables describing the indoor climate such as the air temperature, humidity and carbon dioxide concentration. Control inputs are the energy supply by the heating system which can be used to raise the air temperature, the aperture of the ventilation windows which affects the air exchange between indoor and outdoor air and thus the energy, humidity and carbon dioxide balances inside the greenhouse, and, finally, the carbon dioxide supply rate that can be used to raise the carbon dioxide concentration inside the greenhouse. Since the indoor climate is not fully isolated from the outdoor climate, outdoor climate conditions or so called external inputs such as solar radiation, air temperature, wind speed, humidity and carbon dioxide concentration, have a strong impact on the energy and mass balances of the greenhouse indoor climate.

Crop growth was described by a dynamic model based mainly on the lettuce growth model of Sweeney *et al.* (1981) and combined with the photosynthesis model of Acock *et al.* (1978). The latter model was extended with some relations defined by Goudriaan *et al.* (1985) taking into account the effect of temperature on dry matter production. The details of the model equations, validation experiments and sensitivity analysis of the overall model were described in Van Henten (1994a,b) and Van Henten & Van Straten (1994), respectively. In view of use for optimisation the model was found to give an accurate description of lettuce growth.

The greenhouse climate model is similar to that of Bot (1983) but with a higher degree of aggregation. The details of the model equations consisting of one energy balance for the greenhouse air and two mass balances relating to the humidity and carbon dioxide content of the greenhouse air, as well as validation results were reported in Van Henten (1994b). Validation experiments revealed that apart from some deviations during the early stages of crop growth, temperature, carbon dioxide concentration and humidity were accurately modelled throughout the growing period.

Control input constraints

In horticultural practice, control inputs have magnitude limitations. For example, the amount of heat energy which can be supplied to the greenhouse is limited by the heating capacity of the boiler. Such physical limitations need to be explicitly accounted for in the derivation of the optimal control strategies. They are represented in a straightforward way by the following simple bound constraints

$$u_{min}(t) \leq u(t) \leq u_{max}(t) \qquad (2)$$

where $u_{min}(t)$ and $u_{max}(t)$ are the lower and upper bounds on the control inputs, respectively. In this research, both upper and lower bounds were imposed on the energy supply by the heating system, on the carbon dioxide supply rate and on the aperture of both lee and windward side ventilation windows (Van Henten, 1994b).

State variable constraints

The process model represented by Equation (1) does not constitute an exact and complete description of the process considered. For example, the effects of temperature and humidity on greenhouse crop production are not yet fully understood nor quantified. A climate control algorithm based on such a model may drive the greenhouse climate into a condition known to be unfavourable for crop growth and production. This could be prevented by constraining the greenhouse climate state variables to lie within a bounded region defined by

$$x_{min}(t) \leq x(t) \leq x_{max}(t) \tag{3}$$

where $x_{min}(t)$ and $x_{max}(t)$ are the lower and upper bounds on the state variables, respectively.

In this study, upper bounds were imposed on the relative humidity level and the carbon dioxide concentration in the greenhouse and both upper and lower bound constraints were imposed on the temperature in the greenhouse (Van Henten, 1994b).

The economic performance criterion

For a single harvest crop, the net economic revenue of the controlled crop production process is described by

$$J(u) = \Phi\,(x(t_f),c,t_f) - \int_{t_b}^{t_f} L(x,u,v,c,t)dt \tag{4}$$

where $\Phi\,(x(t_f),c,t_f)$ is the gross economic return of the produce sold, $L(x,u,v,c,t)$ represents the operating costs of the climate conditioning equipment and t_f is the harvest date which is assumed to be fixed.

In The Netherlands, lettuce is sold at auctions in grades based on the fresh weight and on the quality of the produce. Despite the fact that quality aspects have a significant effect on the value of the produce, quantitative relations between the greenhouse climate and crop quality which are needed to derive optimal greenhouse climate control strategies, are not well developed. Therefore, in this study quality aspects were neglected and attention was focused on a quantitative relation between the harvest weight and auction price of a lettuce crop.

Analysis of historical data of the auction price of lettuce dating from 1985 to 1989 revealed that the gross economic return of lettuce production $\Phi\,(x(t_f),c,t_f)$ can be described as a linear function of the harvest fresh weight of lettuce (Van Henten, 1994b). The positive correlation found means that a higher harvest weight obtained, for example, by taking suitable climate control measures, is rewarded by a higher gross economic return. The estimates of the parameters of the linear relation showed a clear annual pattern, of high prices during winter time and lower prices during the summer. Most of the data showed a correlation coefficient of 0.85 or higher. Poor correlation was found during the summer season when the market is saturated by lettuces produced in the open air and the value of the crop is low, irrespective of its harvest weight.

The operational costs of the climate conditioning equipment $L(x,u,v,c,t)$ were essentially determined by the amount of natural gas used for heating the greenhouse and the amount of pure carbon dioxide supplied to the greenhouse. The unit-prices of energy and carbon dioxide were assumed to be constant. The contribution of the electrical equipment used for climate conditioning, such as pumps and valves, to the operating costs were neglected. In this particular case no thermal screens were considered and so their operating costs were not included. Furthermore, it was assumed that other production factors, such as nutrient and water supply, and those not directly related to greenhouse climate control, such as labour, pest and disease control, do not affect the climate control strategies. These are not included in the performance criterion (Van Henten, 1994b).

The optimal control problem

Based on the above, the economic optimal control problem is defined as finding the open-loop control strategy $u^*(t)$ for the whole growing period $[t_b, t_f]$, which maximizes the performance criterion $J(u)$ defined by Equation (4), subject to the differential equation constraints described by Equation (1) and the control and state constraints represented by Equations (2) and (3), given complete knowledge of the auction price and the external inputs $v(t)$ over the whole growing period.

Greenhouse experiment

In an experimental greenhouse at IMAG-DLO a lettuce crop was grown from 21 January 1992 until 17 March 1992. The 4-span Venlo-type experimental greenhouse was oriented East-West and had a floor area of approximately 300 m^2. The roof consisted of single glass panes with twenty half pane ventilation windows on lee and windward sides. A hot water heating system consisting of 4 pipes per span was mounted parallel to the gutters at a height of approximately 2.0 m. In the greenhouse, a distribution network of one hose per span was used to supply carbon dioxide from a storage tank.

Lettuce plants were sown and grown at a nursery in peat blocks and then planted at a density of 18 plants per square meter of soil in a recirculating nutrient film technique system (NFT) consisting of 13 gutters per 2 spans. The commonly grown lettuce cultivar 'Norden' was used.

Using an updated version of the IMAG-DLO computer control system implemented on a Digital PDP-11/73 (Van Meurs, 1980), the greenhouse climate was controlled according to the rules followed in normal horticultural practice. During the first few days of the cultivation period, the day and night temperature set-points were 14 °C. Then, the night temperature was lowered to 10 °C, whereas the day air temperature set-point was at least 14 °C and increased dependent on the solar radiation level. During the day, carbon dioxide was supplied to a maximum concentration of 750 ppm depending on the amount of solar radiation and the opening of the ventilators. With a separate computer, the nutrient solution was controlled to have an EC of around 2.3 mS and a pH of around 6. At regular intervals during the growing period, the grower was advised by a commercial extension service. In this way the crop was grown using standard horticultural practice.

Every 5 to 7 days throughout the growing season, plants were harvested and fresh and dry weights of both roots and shoots, as well as total leaf area, were measured for each plant. Dry weights were obtained after drying the plants in an oven at a temperature of 105 °C for 24 hours.

Using a data logging system connected to the greenhouse climate computer, measurements of the indoor climate, outdoor climate and actuators of the climate conditioning system were recorded. The measurements of the indoor climate included single spot measurements of air temperature and humidity for which dry and wet bulb thermometers (ventilated and radiation shielded) were used. A spatial average value of the carbon dioxide concentration in the greenhouse was measured with a Siemens infrared absorption spectrometer.

Recordings of the actuators of the climate control system included the mean value of the inlet and outlet temperatures of the heating system, the valve position of the carbon dioxide supply system and the window aperture of both lee and windward side ventilation windows.

Outside the greenhouse, solar radiation, air temperature, relative humidity and wind speed were measured with a Kipp solarimeter, dry and wet bulb thermometers (ventilated and radiation shielded) and a cup anemometer, respectively.

Solution of the optimal control problem

Optimal control problems based on non-linear models and non-quadratic performance criteria, such as those defined in this research, are very difficult to solve analytically. Iterative schemes need to be used to achieve a numerical solution of the mathematical problem. In this study, a steepest ascent algorithm based on that of Kirk (1970) was used, but modified to deal with the control input constraints (Van Henten, 1994b). Penalty functions based on those of Pierre (1969) were chosen to cope with the state variable constraints during the numerical solution of the optimal control problem. Numerical solution of the differential equations were obtained using a fourth order Runge-Kutta integration algorithm described by Press *et al.* (1986).

Comparison of optimal control approach with conventional climate control

The measurements of the actuators, the indoor climate and crop growth obtained during the greenhouse experiment in early 1992, represent the behaviour of the controlled process using conventional greenhouse climate strategies defined by the grower. These data have been used as a reference in the comparison with optimal control strategies obtained by simulation.

This case study focused on the slow dynamics in the crop production process. Therefore, the data of the actuators, indoor and outdoor climate were averaged over periods of half an hour. The performance of the grower's approach to greenhouse climate management was evaluated by simulating the system equations (1), neglecting the dynamics of the greenhouse climate and by calculating the value of the performance measure (Equation (4)) and using the energy price and the actual price obtained at the auction.

The performance of the greenhouse climate control strategy of the grower was compared with two optimisation runs in which complete knowledge about the auction price, the energy price and the outdoor climate for the whole growing period was considered. In the first simulation 'Optimal 1', the optimal control problem was solved with time-invariant constraints on air temperature, humidity and carbon dioxide concentration. In greenhouse practice, the operation of the ventilators is determined to a certain extent by requirements on the humidity level in the greenhouse. Because using a time invariant constraint on the relative humidity does not reflect practical management of humidity in greenhouses, in a second run, hereafter referred to as 'Optimal 2', optimal control trajectories were calculated for heating and carbon dioxide supply only, omitting the humidity constraint and using the measured ventilation regime used by the grower, to control the humidity level in the greenhouse.

Results

In Figure 3, performance data of the three control approaches are presented on a relative basis. The data include the simulated harvest weight, the energy consumption, the carbon dioxide consumption and the net economic return which, in the context of the present research, is defined as the difference between the value of the crop at

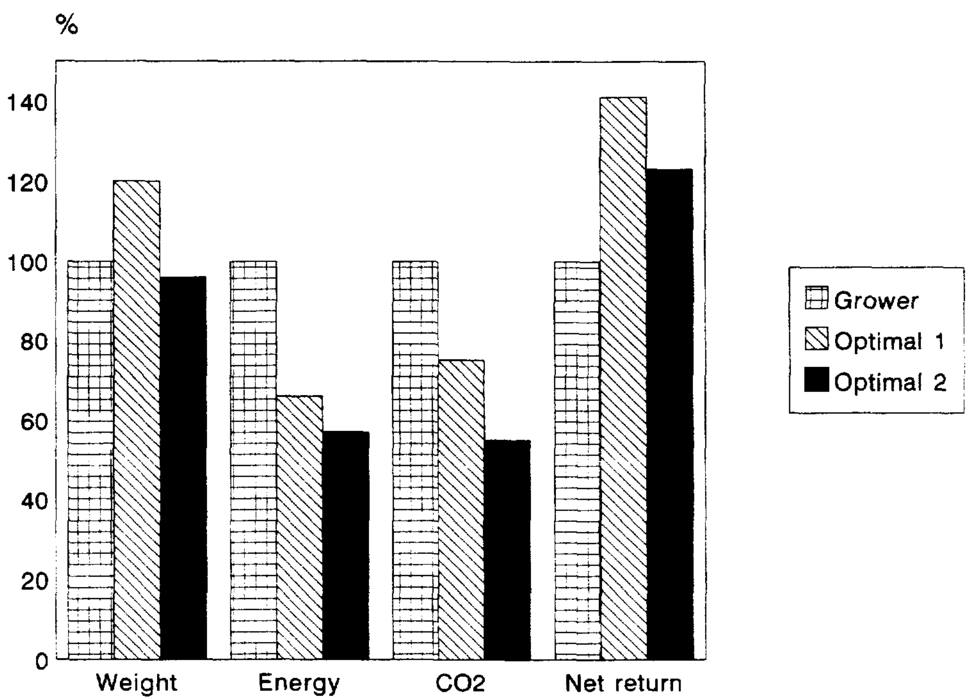

Figure 3. The overall performance of the controlled crop production process using the grower's climate control strategies (Grower), optimal strategies using a humidity constraint (Optimal 1) and optimal strategies using the ventilation regime of the grower (Optimal 2).

harvest time and the climate conditioning costs integrated over the whole growing period.

In terms of net economic return, a considerable difference in performance is observed between the grower's climate control strategies and the optimal control ones. The results of the 'Optimal 1' simulation experiment, in which the relative humidity was limited by an upper bound of 90%, indicate a higher dry matter production and less energy and carbon dioxide consumption compared to the grower's results. In simulation run 'Optimal 2', in which the ventilation strategy of the grower was used to control the relative humidity in the greenhouse, the energy and carbon dioxide consumption are smaller than the counterpart results of the grower. Although fresh weight production in this simulation was approximately the same as that of the grower, the reduced carbon dioxide and energy consumption yielded a higher net economic return. These simulations show that with optimal control, energy and carbon dioxide are used more efficiently.

Table 1 gives the total carbon dioxide and energy consumptions, and ventilation exchanges over the full production cycle for the three different control strategies. In simulation 'Optimal 1', a lower ventilation rate during the day was calculated than was used by the grower. However at night, optimal ventilation was much higher. Although in simulation 'Optimal 1' less carbon dioxide was consumed than the grower had used, the reduced ventilation rate during the day resulted in a higher carbon dioxide concentration in the greenhouse, thus yielding the observed higher fresh weight production. Another distinct difference between the optimal and grower's climate control strategies is the reduced energy consumption during the day and, to a lesser extent, during the night (Table 1). Using the ventilation regime of the grower (Optimal 2), during both day and night less energy and about half the amount of carbon dioxide were used.

Further insight into the differences between the grower's management strategies and the optimal control strategies in greenhouse climate management is obtained by comparing the measured and calculated control and state trajectories.

Averaged measured data of solar radiation are presented in Figure 4 for a period of 5 representative days. The time course of carbon dioxide supply, ventilation air exchange and heat consumption of the grower's experiment and those corresponding to the 'Optimal 1' simulation, are shown in Figure 5. The simulated greenhouse climate

Table 1. Total carbon dioxide consumption, energy consumption and ventilation during the whole growing period in early 1992 with greenhouse climate control according to the grower (Grower), optimal control with humidity constraint (Optimal 1), optimal control without humidity constraint using the measured ventilation trajectories implemented by the grower (Optimal 2).

	Carbon dioxide consumption (kg m^{-2})		Energy consumption (MJ m^{-2})		Ventilation (m^3 m^{-2})	
	Day	Night	Day	Night	Day	Night
Grower	1.23	-	105	127	5439	2955
Optimal 1	0.94	-	43	110	3519	6298
Optimal 2	0.68	-	45	88	5439	2955

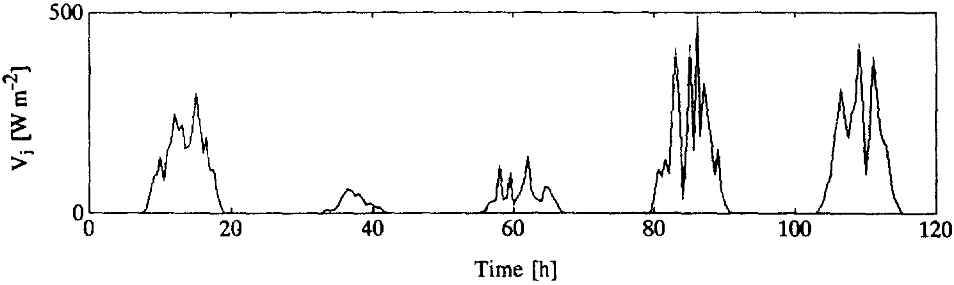

Figure 4. Solar radiation (V_i) over a five days period.

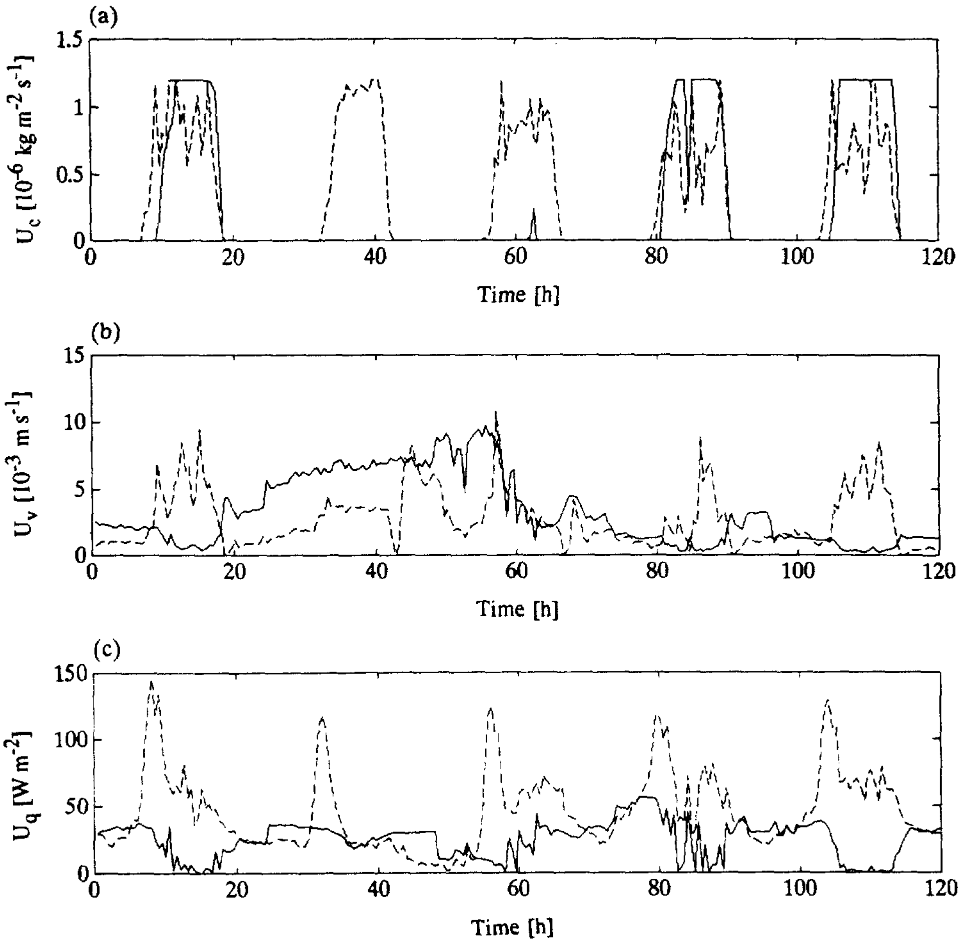

Figure 5. Trajectories of carbon dioxide supply rate U_c (a), ventilation rate U_v (b) and heating energy U_q (c), corresponding to the grower (dashed line) and to optimal control strategy 'Optimal 1' (solid line).

variables driven by the external climatic conditions of Figure 4 and control inputs of Figure 5, are presented in Figure 6.

Figures 4 to 6 help to clarify some of the differences found in Figure 3 and Table 1. For example, Figure 5a shows that using optimal control strategies, the carbon dioxide supply responds to the solar radiation in a different way than that using grower's control strategies. Due to the unfavourable radiation conditions as well as the high ventilation rates during days 2 and 3, in the optimal control approach the supply of carbon dioxide to the greenhouse air was not considered profitable under these circumstances. In the greenhouse climate control strategy implemented by the grower, the carbon dioxide set-point was adapted to the solar radiation as well as to the ventilation rate (Corver, personal communication). The carbon dioxide supply in

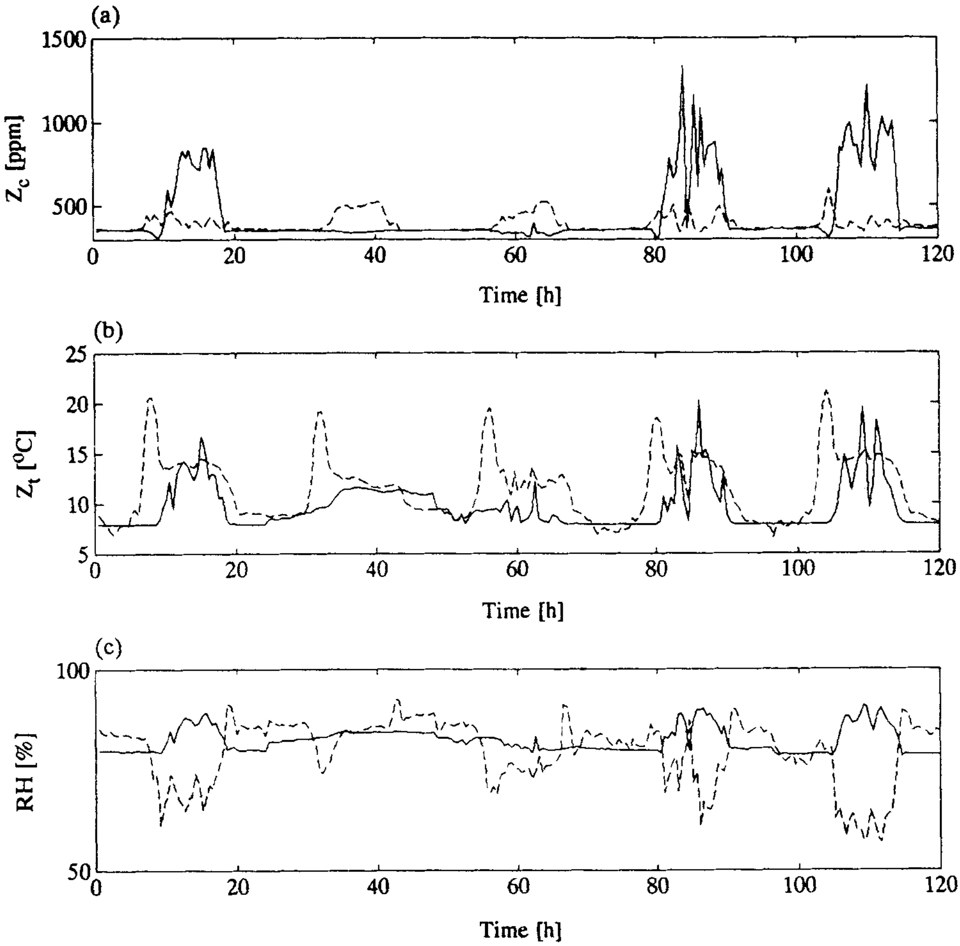

Figure 6. Trajectories of carbon dioxide concentration Z_c (a), air temperature Z_t (b) and relative humidity RH (c), corresponding to the grower's climate control strategy (dashed line) and to the optimal control strategy 'Optimal 1' (solid line).

days 2 and 3 was more than that using optimal control strategies. On the contrary, the control strategy implemented by the grower did not enrich adequately with carbon dioxide under the favourable radiation conditions of days 4 and 5. During this period, the grower seemed to prefer a high ventilation rate to reduce the relative humidity in the greenhouse (see Figures 5b and 6c) and consequently reduced the carbon dioxide supply rate to prevent excessive losses of carbon dioxide to the outside air.

In Figure 6a it is shown that when using optimal control strategies under favourable circumstances, the carbon dioxide concentration in the greenhouse exceeded 1000 ppm whereas the grower used an upper limit of 750 ppm to limit the carbon dioxide consumption (Corver, personal communication).

The high ventilation regime implemented by the grower during the day was mainly intended to reduce the humidity level in the greenhouse and consequently to prevent fungal diseases and physiological damage, such as marginal spot (Corver, personal communication). A relative humidity as low as 60% can be seen in Figure 6c. In the optimal control approach, however, the ventilation rate was reduced during the day to achieve a more efficient use of the carbon dioxide supplied. Consequently, a higher relative humidity (90%) was encountered than in practice. At night the differences in the humidity levels were found to be rather small.

With regards to the air temperature in the greenhouse, the grower used a minimum value of 14 °C during the day. On average, this set-point was almost equivalent to the calculated optimal air temperature during the five days shown. Due to the high ventilation regime used by the grower during the day, more heating energy was needed to realise the air temperature set-point which explains to a certain extent the high day time energy consumption observed in Table 1. The optimal air temperature trajectories in Figure 6b also suggest that adjustment of the indoor temperature to the outside climatic conditions such as solar radiation may improve the efficiency of greenhouse climate management.

The difference in energy consumption at night between the grower's strategies and the optimal control strategies is partly explained by the fact that, especially during the first two weeks of the growing period, the grower used an air temperature set-point of 14 °C. Further analysis revealed that with the particular crop growth model used, heating is not considered profitable at night (Van Henten, 1994b). The resulting high air temperature has a negative effect on the dry matter production due to increased maintenance respiration at high temperatures. Therefore at night the air temperature was determined by the lower bound constraint so that values as low as 7 °C were simulated. Also in the optimal control approach, the heat pulse at sun rise, implemented by the grower to 'activate' the crop, was not considered economically feasible since the possible benefits in terms of crop quantity or quality of this approach were not described by the model used. Clearly, the heat pulse implemented by the grower contributed to a higher energy consumption.

In a qualitative sense, the optimal control strategies used in simulation 'Optimal 2' (not shown) yielded the same results as those calculated in simulation 'Optimal 1'. The improved efficiency of greenhouse climate control was achieved by a more efficient use of carbon dioxide and a reduction of the energy consumption due to the absence of the heat pulse at sun rise and the lower air temperature at night. Although less heat energy was used during the day, even though the ventilation regime of the grower was adopted, only a slightly higher humidity level in the greenhouse was reached than with the optimal control strategies.

Discussion

The differences in efficiency between the optimal control strategies and the grower's control strategies for greenhouse climate management are significant and one may argue whether such improvements can be achieved in practice. The following observations are made.

Model accuracy and model uncertainty

Albeit the crop growth model used for the calculation of the optimal control strategies quite accurately simulates crop fresh weight production, it does not account for other aspects related to crop quality, such as head formation, and the occurrence of physiological damage and fungal diseases under humid conditions. These deficiencies may affect the favourable results of the optimization for example in the following way. In greenhouse management practice, the high humidity levels calculated in simulation 'Optimal 1' (in which the time-invariant constraint on the humidity was imposed) may be unfavourable for the quality of a lettuce crop. However, in simulation 'Optimal 2' (in which the ventilation regime adopted by the grower was used to control the humidity level) it was shown that carbon dioxide as well as heating energy were still used more efficiently. Furthermore, the optimal carbon dioxide concentrations and air temperatures, calculated in 'Optimal 1', were reasonable and are not expected to have an adverse effect on lettuce growth. Therefore, the major trends of the results reported in this paper are still expected to hold.

Still, the optimal control approach strongly relies on an appropriate model of the process to be controlled. Therefore, to expand the ideas presented in this paper, further research in the field of modelling the greenhouse crop production process is required. But also, feedback control based on moving horizon optimal control techniques can effectively deal with uncertainty and model inaccuracy in non-linear optimal control problems (e.g. Yang & Polak, 1993).

Uncertainty in predictions of outdoor climate and auction prices

The optimal control simulations represented an ideal situation since the control trajectories were calculated after the greenhouse experiment had ended using complete knowledge about the outside climatic conditions as well as the auction price. In practice, these external factors have to be predicted and inaccuracies in these predictions may reduce the benefits of optimal control suggested in this paper. Still, they are not expected to alter the major trends of these results.

Although further research is needed, these uncertainty issues have already received attention in the literature. The potential of predicting auction prices was investigated by Van Henten (1994b). An analysis of the auction price of lettuce revealed that the estimates of the parameters used to describe the linear relation between harvest weight and product price of lettuce, showed a very distinct seasonal pattern with a high auto-correlation function which offers the opportunity to predict the auction price using for example an auto-regressive model. Favourable results of short term weather forecasting using time series analysis were reported by Brown *et al.* (1984) and Huang & Chalabi (1994). A potential benefit is expected from the conjunction of these short term weather forecasts with long term meteorological weather forecasts. Also, as stated earlier, moving horizon optimal control techniques can effectively deal with uncertainty in non-linear optimal control problems (e.g. Yang & Polak, 1993). This was confirmed by Tap *et al.* (1996) who reported on the effectiveness of this approach in dealing with the uncertainty in the outdoor climate conditions.

Constraints

It appears that constraints, especially the humidity ones, play an important role in optimal greenhouse climate control. Hence, a more accurate assessment of the effect of humidity and other micro-climatic variables on the quality and quantity of crop production, either in terms of model equations or in terms of (time-variant) constraints is required.

The influence of the greenhouse climate dynamics

In the present analysis the greenhouse climate dynamics were neglected based on the premise that only the slow trends in the outside climatic conditions were considered. In reality, rapid fluctuations in the outside climatic conditions do occur and their impact on optimal greenhouse climate management has not been considered in this study. Investigation of the effect of this assumption, which is commonly made in greenhouse climate optimisation (e.g. Critten, 1991; Seginer, 1991; Van Henten & Bontsema, 1991; Bailey & Chalabi, 1994), has not yet been conclusive (Tap *et al.*, 1993; Van Henten, 1994b; Ioslovich *et al.*, 1995). Therefore the main results obtained in this study are believed to hold. However, when on-line optimal control of the greenhouse climate is considered the rapid fluctuations in the process and thus, for reasons of stability, the greenhouse climate dynamics have to be accounted for. A computational framework based on a two time-scale decomposition of the greenhouse climate control described in Van Henten & Bontsema (1992, 1996) and Van Henten (1994b), deals effectively with the greenhouse climate dynamics as well. The applicability of this approach has been confirmed by Tap *et al.* (1996).

On-line control

In the recent past the considerable computer power required for the numerical solution of the optimal control problem has been an obstacle for the practical on-line implementation of optimal greenhouse control strategies. Recently, on-line control experiments convincingly showed that with the current performance of relatively inexpensive digital computers this obstacle is circumvented (Van Meurs & Van Henten, 1994; Tap *et al.*, 1996).

Conclusion

In this paper a comparative analysis, supported by experimental work, was carried out to determine the potential improvement in economics and energy efficiency in using optimal control strategies in greenhouse climate management over a whole growing season of a lettuce crop. The results obtained support the conclusion that a considerable improvement in the efficiency of greenhouse climate management is possible. This improvement may well exceed 15%. Clearly, the final test of the merits of optimal control have to be obtained in full scale validation experiments in the greenhouse.

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