THREE TIME-SCALE DIGITAL OPTIMAL RECEDING HORIZON CONTROL OF THE CLIMATE IN A GREENHOUSE WITH A HEAT STORAGE TANK

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Abstract : The design, implementation and some preliminary experimental results of a three time-scale digital optimal receding horizon control system are presented, to control the climate in a greenhouse with a heat storage tank. The design is based on a dynamic model that contains a sophisticated description of the greenhouse, including a heat storage tank, and a more simple description of a crop. The digital optimal receding horizon controller design uses recently developed ideas to overcome problems associated with feedback, the different time scales of the greenhouse crop system and the large influence of the weather which cannot be predicted accurately over the whole growing period of the crop. These problems are overcome by a three time scale decomposition and the use of a short term so called lazy man weather prediction, a commercially available weather prediction over 24 hours, and a long term weather prediction which equals the average weather over a couple of years. The algorithm used to solve the decomposed optimal control problems is a recently developed algorithm that is able to explicitly consider the possibly digital nature of the controller and the continuous-time (inter-sample) behaviour of the system. Therefore it does not require the selection of a small sampling interval. It is shown how the selection of two sampling intervals, at the level of the smallest time scale of the control system, can be used to improve the design and efficiency of the control algorithm.

Keywords: Receding horizon control, Digital optimal control, Singular perturbations

1. INTRODUCTION

Greenhouses with a heat storage tank offer the possibility to supply CO2, which is a by product of the burner of the heating system, at any moment in time rather then at those moments which require heating. If CO2 supply is desired but heating is not, the heat produced by the heater is stored and can be used in a later stage to heat the greenhouse. Due to the importance of CO2 supply to enhance crop growth heat storage tanks have become widespread in the Netherlands. To the best knowledge of the authors in this paper for the first time a dynamic model is presented of a greenhouse which includes a heat storage tank. As demonstrated in this paper the presence of the heat storage tank has important consequences for the control system design.

In the last decade research concerning the modelling of greenhouses and crops has been put to practice by researchers in the area of control engineering (Seginer 1989, Van Henten 1994, Tap 1994). An important contribution in this area was made by Van Henten (1994). He recognised that an optimal control approach enables the exploitation of scientific knowledge concerning greenhouses and crops to design a highly automated and sophisticated so called optimal control system. Opposite to the current climate control systems the optimal control system has a very limited number of settings (around 10 versus 100-300) which all have a clear meaning and can be manipulated by the grower to improve the result. In addition to this, the effect of the change of these settings can be presented to the grower immediately and in a transparent manner. The effects shown to the grower relate both to crop growth and the costs of climate control.

Van Henten (1994) also recognised and solved problems associated with the different time-scales of the greenhouse-crop dynamics. Although a time-scale decomposition is known to solve this problem (Freedman and Kaplan, 1976) its application in the case of greenhouse climate control is hampered by the large influence of external variables, namely the weather, which changes rapidly. This causes a violation of the assumption that, except near the initial and final stages of control, the fast system dynamics are in equilibrium which underlies the time scale decomposition. Van Henten's work (1994) indicates that if nevertheless the time-scale decomposition is applied the loss of performance is very modest. Finally Van Henten (1994) presented the general structure of an optimal greenhouse control system which realises feedback through application of a receding horizon optimal controller operating at the smallest time scale using short term weather predictions. This receding horizon controller uses information obtained from solutions of optimal control problems related to the other time-scales. The latter can be solved off-line or at a much slower rate but they need weather predictions over longer periods.

The work of Van Henten (1994) was continued by Tap (1994), who implemented the structure proposed by Van Henten, but instead of lettuce considered tomato crops. Tap used an algorithm developed by Van Willigenburg (1995) to solve digital non-linear optimal control problems. An important special feature of this algorithm is that it explicitly considers the digital nature of the controller and the continuous-time (inter-sample) behaviour of the system. This circumvents the demand to choose the sampling interval sufficiently small. In implementing the receding horizon optimal controller Tap showed that the use of the so called 'lazy man weather prediction', which assumes the future weather to stay equal to the most recent measured weather, is to be preferred over other weather predictions, and that a horizon of one hour is approximately the best choice (Tap *et.al* 1996). Tap *et.al* (1996) distinguished two time scales in the optimal control system design, but mentioned that, due to the buffer in the tomato crop model, three time-scales would be a better choice.

In this paper we show how the presence of the heat storage tank in the greenhouse also results in an extra time-scale. Depending on the time-scales already present this may result in an extra time-scale in the optimal control system design. Furthermore we show how the freedom in choosing the sampling interval in the digital optimal control algorithm of Van Willigenburg (1995), can be exploited to improve the performance of the receding horizon optimal controller which operates at the smallest time-scale. Specifically it is shown that the 'lazy man weather prediction' very well fits the choice of a relatively large sampling interval at the computational level of the receding horizon controller, and how this choice improves the numerical performance of the optimal control system. Finally some preliminary results obtained with the digital optimal control system, which was implemented in a greenhouse at the Wageningen University and Research Centre are presented. They indicate the applicability and advantages of the optimal controller structure proposed by Van Henten (1994) over conventional controller structures.

2. THE GREENHOUSE AND CROP MODEL

The greenhouse crop model contains a detailed description of the greenhouse dynamics, represented by 13 state variables and a more simple one for the crop, represented by only 1 state variable. The state variables of the model are,

1 temperature of greenhouse cover
2 temperature of greenhouse air
3 temperature of the crop
4 temperature of the soil
5 temperature of the upper heating pipes
6 temperature of the lower heating pipes
7-11 temperatures of 5 layers of water inside the heat buffer
12 concentration of carbon dioxide (CO_2) inside the greenhouse
13 humidity of the air inside the greenhouse
14 dry weight of the crop

There are 6 control variables,

1 window opening at the lee-side
2 window opening at the winward-side
3 valve opening of the CO_2 produced by the burner of the heating system
4 valve opening of water coming from the heating system and supplied either to the greenhouse or the heat buffer
5 valve opening of the upper heating pipes
6 valve opening of the lower heating pipes

If the 4th control variable is activated, i.e. if the valve of the water coming from the heating system is not fully closed, it is assumed that the heating system produces CO_2. Only then the use of the 3rd control variable results in CO_2 dosage, otherwise this control variable has no influence. Depending on the values of control variables 4-6 part of the flow from the heater enters the heat buffer as long as it is not full. The heat buffer is assumed to be full if the last layer reaches a temperature of 80 ^oC. In this case the valve opening 4 fully determines the flow into the lower heating system and overrules the valve opening 6, which in practice is adjusted to the opening of 4. This overruling takes place smoothly starting at a temperature of 75 ^oC of the last layer of the heat buffer and is complete at a temperature of 80 ^oC. A detailed description of the model can be found in Van Henten (1989) and in Van Meurs and Van Willigenburg (1999). Basically the model consists of a detailed description of the transport phenomena which take place between the state variables. These phenomena are partly derived from the work of de Jong (1990).

The increase of crop dry weight is assumed to be proportional to the net photosynthesis which equals the gross photosynthesis minus respiration. The gross photosynthesis is computed according to H. Gijssen (1994) which is a modified version of the so called Farquar model. To apply optimal control the model is presented in the following general form of first-order differential equations,

$$\dot{x} = f(x,u,d) \qquad (1)$$

where $x \in R^n$ is a vector containing the state variables, $u \in R^m$ is a vector containing the control variables, $d \in R^e$ is a vector containing the external variables which in our model are the outside air and sky temperature, wet bulb temperature, outside humidity and CO_2 concentration, incoming short wave radiation, and wind speed.

3. THE PERFORMANCE INDEX

The performance index is determined by the value of crop dry weight on the one hand and by energy costs to maintain the greenhouse climate on the other hand. Because the crop model is only valid in a limited climate range, penalties are also introduced in the performance index to prevent the climate from entering unfavourable regions which damage the crop while this damage is not described by the model. The performance index has the following general form,

$$J(u(t)) = \Phi\left(x\left(t_f\right)\right) + \int_{t_0}^{t_f} L(x,u,d,t)dt \qquad (2)$$

The first term on the right in equation (2) in our case is used to reflect the value of dry weight at the end of the optimisation period $\left[t_0, t_f\right]$,

$$\Phi\left(x\left(t_f\right)\right) = -p_d x_{14}\left(t_f\right) \qquad (2.1)$$

where p_d represents the value of a unit of crop dry weight and $x_{14}\left(t_f\right)$ represents the amount of crop dry weight, i.e. the value of the 14th state variable at the final time t_f of the optimisation. The minus sign is due to the minimisation of the performance index. The second term on the right in equation (2) is used to represent the so called running costs which are related to energy consumption and penalties associated with violations of bounds associated to the greenhouse climate.

$$L(x,u,d,t) = \sum_{i=1}^{6} a_i L_i(x,u,d) \qquad (2.2)$$

In equation (2.2) for $i = 1,2,..,6$ a_i represents the penalty or price associated to L_i which represents the momentary value of energy consumption or the momentary violation of a bound associated to the greenhouse climate. As an example of the latter consider L_1 the penalty associated to a violation of the upper or lower bound for the greenhouse air temperature x_2. L_1 is as follows,

$$\begin{aligned} &L_1 = 0 \text{ if } x_2^l \le x_2 \le x_2^u \\ &L_1 = a_1\left(x_2 - x_2^u\right) \text{ if } x_2 > x_2^u \\ &L_1 = a_1\left(x_2^l - x_2\right) \text{ if } x_2 < x_2^l \end{aligned} \qquad (2.3)$$

where $a_1 > 0$ represents the penalty or price associated to the violation of the upper bound x_2^u or the lower bound x_2^l associated to the greenhouse air temperature x_2. Similarly there are penalties for the violation of upper and lower bounds for the air humidity inside the greenhouse and also for the CO_2 concentration in the greenhouse which is only limited from above. Furthermore there are penalties for violations of a temperature and humidity integral which are introduced as additional state variables. Consider x_{15} which is the temperature integral defined by,

$$\dot{x}_{15} = x_2 - x_2^r,\ x_{15}\left(t_0\right) = 0 \qquad (3)$$

In equation (3) x_2^r represents an ideal constant reference value for the greenhouse air temperature. So x_{15} measures deviations from this ideal temperature cumulatively. The idea behind penalising the violation of bounds on this temperature integral is that the plant can temporarily withstand deviations from the ideal temperature x_2^r up till a certain level. Furthermore negative deviations can be compensated for by positive deviations (De Koning, 1996). Similar arguments hold for the humidity integral measured by x_{16}. This completes the description of the performance index.

The choice of the bounds and also of the prices and penalties a_i, $i = 1,2,..,6$ associated to violations of these bounds clearly are critical and influence the performance. In our case the choice is based on experience and several simulation experiments. It would be much better to obtain them from a sensitivity analysis.

The bounds, prices and penalties make up the settings of the optimal control system and all have a clear meaning and influence on the behaviour of the optimal control system.

4. DESIGN AND IMPLEMENTATION OF A THREE TIME SCALE RECEDING HORIZON OPTIMAL CONTROLLER

In this section a three time-scale receding horizon optimal controller design is proposed and discussed to deal with the uncertainty of the model and the weather predictions as well as to resolve the problem of different time scales and the associated ill-conditioning and low efficiency of the on-line controller computations. In actual practice two time-scales of this controller have been implemented at a greenhouse of the Wageningen University and Research Centre. Unfortunately at present this greenhouse is not equipped with a heat storage tank. At the time of writing the implemented controller is running and the buffer is deactivated. In this paper we present experimental results obtained with this controller. These results indicate that the controller performs well in the sense that unexpected control actions, due to programming errors, modelling errors, or ill settings of the bounds for several state variables, described in the previous section, and the associated penalty factors, do not occur.

For a detailed justification and description of a greenhouse climate controller with different time scales and several types of weather prediction we refer to Van Henten (1994) and Tap (1994). In addition to this we will consider specifically design aspects related to the digital nature of the on-line receding horizon optimal controller which operates at the smallest time scale. At the level of the largest time-scale only the dynamics of the crop are considered while the buffer and greenhouse are assumed to be static. At this level a seasonal continuous-time optimal control problem must be formulated and solved (Van Henten, 1994). The problem formulation includes a long term weather prediction consisting of average weather over several years. The optimal state and costate time evolutions are needed to determine the performance index of the optimal control problem at the level of the intermediate time-scale (Van Henten, 1994). At this level the dynamics of the buffer are considered while the greenhouse dynamics are assumed to be static. In solving the continuous-time optimal control problem at this level, the dynamics of the crop do not have to be integrated, thereby circumventing ill-conditioning of the integration. Without having to be integrated the crop dynamics do play a part in the determination of the performance index (Van Henten, 1994). At this intermediate time-scale level weather predictions over one or a few days are needed which are available commercially. The continuous-time optimal control problems at the two mentioned time-scale levels can be solved off-line.

At the third level, i.e. the level of the smallest time-scale, the greenhouse dynamics are considered, while the buffer and crop are considered to be static. At this level a receding horizon *digital* optimal controller is used that solves *on-line* associated *digital optimal control problems*, as defined in Van Willigenburg (1995), which explicitly consider the inter-sample continuous-time behaviour of the system and the digital nature of the controller. Let T_s denote the sampling interval of the digital optimal receding horizon controller. Then

$$iT_s,\ i = 0,1,..,\qquad (3)$$

are the time instants at which the receding horizon controller updates the control. Through the use of a zero-order hold the control is kept constant in between $\left[iT_s,(i+1)T_s\right)$ i.e.,

$$u(t) = u(iT_s),\ t \in \left[iT_s,(i+1)T_s\right),\ i = 0,1,...\qquad (4)$$

Within each time interval $\left[iT_s,(i+1)T_s\right)$ $i = 0,1,..$ based on the controls and measurements up to iT_s the digital optimal receding horizon controller computes

$$u\big((i+1)T_s\big),\ u\big((i+1)T_s + t_s\big),..,u\big((i+1)T_s + (N-1)t_s\big),\qquad (5)$$

the digital optimal control sequence for the associated digital optimal control problem defined over the time-interval

$$\left[(i+1)T_s,(i+1)T_s + Nt_s\right],\qquad (6)$$

where t_s denotes the sampling period used in computing the digital optimal control over the time interval (6) with length Nt_s. So Nt_s is the horizon length of the digital optimal receding horizon controller. Note that T_s and t_s may be chosen differently. T_s determines the rate by which the receding horizon controller updates the control actually applied to the system. Thus the selection of T_s depends on how fast one wants the control to be updated. On the other hand t_s determines the sampling period used in *computing* the digital optimal control sequence (5), of which only the first one, i.e. $u\big((i+1)T_s\big)$, is actually applied to the system. Therefore the accurate determination of $u\big((i+1)T_s\big)$ is crucial for a receding horizon optimal controller. By enlarging t_s and decreasing N in (6) the horizon Nt_s of the receding horizon controller can be kept constant while *increasing the sensitivity* of the performance to the value $u\big((i+1)T_s\big)$. This in turn improves the *accuracy* by which $u\big((i+1)T_s\big)$ is computed. On the other hand enlarging t_s and decreasing N in (6) means that dynamic effects inside t_s cannot be fully exploited. But this would not be possible anyway due to the lazy man weather prediction which assumes the weather to be constant over the time-interval (6).

Summarising, there are two reasons why at the lowest level a digital optimal control problem is considered. 1) The on-line control is performed by a digital computer. 2) By manipulating t_s and N in (6) the accuracy of the control computation $u\big((i+1)T_s\big)$ in (5), and thus of the receding horizon controller performance, can be improved, *without changing the performance index and the associated control objectives*. In our implementation T_s equals 2 minutes, t_s 20 minutes and N equals 3. The choice of T_s is based on the speed of light variations which is the most fast changing external variable which also changes faster than all the state variables of the model. The choice of t_s, a multitude of which must be equal to the horizon of 1 hour of the receding horizon controller, is governed by the arguments mentioned earlier in this section.

The state information is incomplete since the state of the crop is not measured. The state variables that represent the greenhouse climate are all measured and used as corresponding estimates of these state variables. The state-variables of the crop, which are needed to compute the control, are fully determined by the crop model which is driven by the estimated state variables of the greenhouse model. It is expected that crop measurements will enable a significant improvement of the estimates of the state variables of the crop. Although crop measurements will be taken at a slower rate than the other measurements, they can still be used to design a state estimator. This design is similar to the state estimator design for asynchronously sampled linear systems [10].

Experimental results obtained over four consecutive days are presented in figure 1. Several remarks concerning the data are in order. In between 600 and 1000 minutes CO_2 is often supplied while the windows are open because, opposite to what one might suspect, this is profitable due to the high radiation that occurs at the same time. The windows must be opened to prevent the violation of the upper bound for the greenhouse air temperature. We also have to note that the crop growth was not measured but the data represent the cumulative crop growth computed by the internal crop model. Because, except in between 600 and 1000 minutes, the weather was rather poor for crop growth, the costs, when integrated over the four days, are positive. So momentarily no profit is made. Note however that the costs also include "fictitious costs" associated to the violation of upper and lower bounds of several climate variables. The windows are opened and closed very often. If this is undesirable, for reasons not described by the model, these reasons must somehow be incorporated in the model and additional costs should be associated to this. Finally inspection of the crops grown in the optimal controlled compartment and in a conventionally controlled compartment showed no significant differences.

5. CONCLUSIONS

The design and implementation of a three time-scale digital optimal receding horizon control system has been described, for the control of a greenhouse with a heat storage tank. To our best knowledge this is the first time a greenhouse model including a heat storage tank has been presented. The presence of the heat storage tank introduces an intermediate time-scale in the greenhouse-crop model, if this time-scale was not already introduced by the presence of e.g. a buffer in the crop model. The advantages of using a digital optimal receding horizon controller, at the level of the smallest time-scale, was discussed. This controller allows for the selection of two sampling periods inside the control system, which can be used to enhance the control system performance.

Experience obtained with the implemented control system at one of the greenhouses of the Wageningen Research Centre revealed that the optimal control approach makes it very easy to track down software and hardware errors which are inevitably present in a first implementation. By examining the input and output of the greenhouse and crop model, as well as monitoring the cause in time of the performance index, we were always able to establish very quickly where software, hardware or measurement errors occurred.

The greenhouse manager, who is in charge of the greenhouse management and control, was very enthousiastic about our optimal control system, since its settings, such as the bounds for several state variables and the associated penalties, are very transparent and very limited in number. In addition to this their effect on the net income of the grower and also their effect on crop growth and heating costs, could be displayed immediately. One could state that the settings of an optimal greenhouse control system are much more natural, transparent and limited in number than those of a conventional greenhouse control system. Furthermore the use of dynamic models with a clear physical or plant physiological meaning makes it relatively easy to adapt the control system design if changes to the greenhouse or crop are made such as the addition of a heat storage. Also the optimal control approach enables full exploitation of scientific knowledge concerning greenhouse and crop behaviour. The very preliminary experimental results indicate that the optimal control system does not perform worse than the conventional control system.

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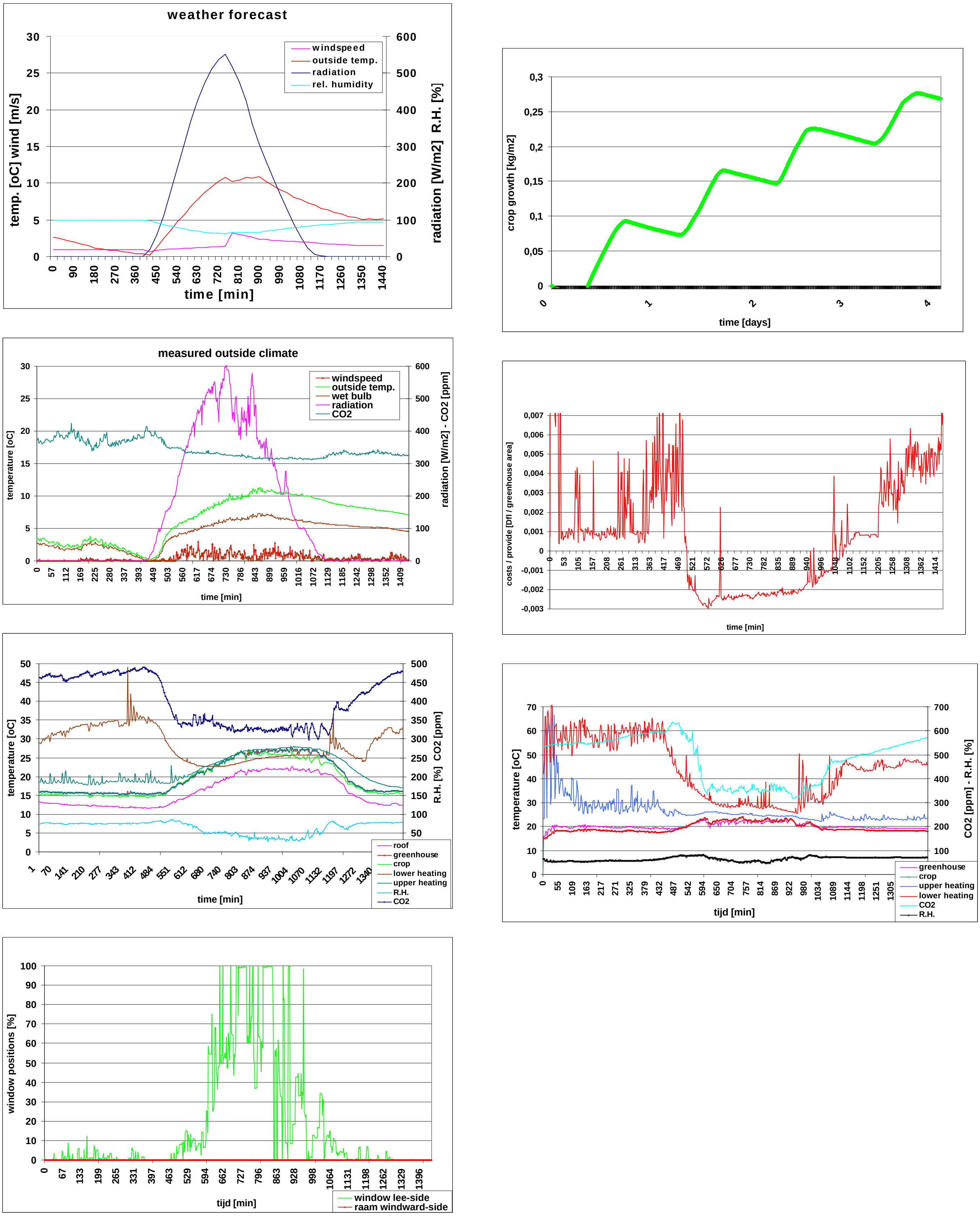
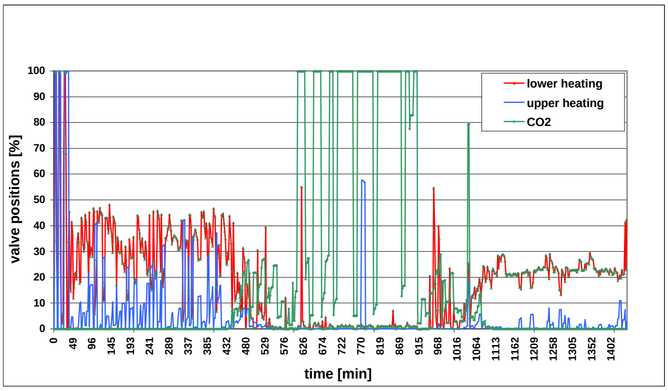
Figure 1: Optimal control and state trajectory, the weather forecast and the measured outside weather conditions




valve positions [%]
100
90
80
70
60
50
40
30
20
10
0
time [min]
0
49
96
145
193
241
289
337
385
432
480
529
576
626
674
722
770
819
869
915
968
1016
1064
1113
1162
1209
1258
1305
1352
1402
lower heating
upper heating
CO2