AUTOMATIC RECEDING HORIZON OPTIMAL CONTROL OF THE NATURAL VENTILATION PROCESS IN CATTLE BARNS

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Abstract: The design and simulation results of an automatic receding horizon optimal controller (RHOC), that controls the ventilation and the associated climate in cattle barns through variable valve openings, are presented. The design is based on so called comfort parameters for cattle in barns and a dynamic model, originally developed using a finite-element programming package, that describes the natural ventilation and the associated climate in cattle barns. In addition to the model the RHOC uses the so called 'lazy man weather prediction' to control the ventilation and the associated climate in the barn. The 'lazy man weather prediction', which assumes the future weather to stay equal to the most recent measurements, is to be preferred over other weather predictions. The choice of the optimisation horizon length and the implementation of the RHOC are discussed and illustrated. The simulation results illustrate the high potential of an RHOC to control the ventilation and the associated climate in cattle barns. When compared to optimal open loop control over the full horizon the loss of performance of the closed loop RHOC, caused by the receding horizon, is limited to about 5 percent. In practice closed loop control is necessary to counteract disturbances and modelling errors. *Copyright © 2000 IFAC*

Keywords: Receding horizon optimal control, dairy, climate control, comfort parameters

1. INTRODUCTION

The climate in livestock buildings has a great influence on the production, fertility and maintenance processes of the animals. Health problems and production losses can occur when the climate in barns is not adjusted properly to the animals. Younger animals and animals with a higher production are more sensitive to an ill-conditioned climate. Therefore it is of great importance to control the indoor climate to meet the so called comfort parameters of the animals.

In the Netherlands most of the barns for cows are naturally ventilated and controlled by hand. It is difficult for an individual farmer to control this ventilation process, because this process is very dependent on wind direction and wind speed. Since the comfort parameters allow for relatively large variations in the climate, in practice automated climate control is often absent. As a result the comfort parameters can be violated, especially during extreme or fast changing weather conditions.

By making use of an automatic control system the climate is permanently monitored and controlled. If optimal control theory is used to design the control system then weather predictions and scientific models that describe the influence of outside weather on the indoor climate can be exploited, to optimally meet the comfort parameters. This paper presents the design of an automatic RHOC. At every moment in time this controller uses the actually measured outside weather and indoor climate conditions, together with a mathematical model of the barn and a simple weather prediction, to calculate the control over the next sampling period, such that the comfort parameters are optimally met. The design is similar to that presented in Tap *et al.* (1999) which deals with optimal control of greenhouse climate. The performance of the control system is tested and verified in simulation.

2. COMFORT PARAMETERS AND ZONES

The following comfort parameters are used to determine the desired indoor climate: 1) air temperature 2) relative humidity 3) air movement and 4) air composition. Dairy cows tolerate a wide range of the air temperature. The aim is to have an air temperature that differs less then 2-5 ^{0}C with the outside temperature within the comfort zone of the cows. This avoids draught (Roovers, 1997). In this case it is possible to realise a high ventilation rate. Besides this air temperature should stay within the comfort zone of the cows, that is roughly between -10 and 25 ^{0}C.

A too high relative humidity in a barn could lead to condensation on the construction, disorders to the bronchial tubes of animals and creates a better environment for microbes to develop. A too low relative humidity irritates and damages the mucous membranes. Practical values for the upper and lower limit of humidity are 80 % and 50% (Klimaat, 1992). It is also possible to use the standard as suggested by CIGR (1984).

The air movement in the barn as a result of convective streams and ventilation has to be less than 0,2 m/s in the neighbourhood of the animals (Ooster, 1993). The incoming fresh air has to enter evenly distributed over the inlet openings, and must quickly mix uniformly with the air already present in the barn, to make sure that all the animals obtain fresh air and draught air is prevented. The amount of fresh air has to be adjusted to the needs of the animals (Albright, 1990). The incoming air has to follow the roof for a while and then must slowly drop down. This creates a circular air flow, a part of which leaves through the ridge. This broad and calm circulation gives the incoming air time to warm up while the air speed near the animals is low (Wientjes, 1998). Considering the health of both the people and the animals in the barn, the composition of the air in the building should not contain harmful concentrations of gas. Among the harmful gasses are ammonia, carbon monoxide, carbon dioxide and sulphur hydrogen. Table 1 tabulates the recommended maximum concentrations of gasses used in the control procedure.

Table 1 Maximal allowed gas concentrations in barns (CIGR, 1984), (Ooster, 1993).

Gas	Maximum concentration (ppm)	MAK (ppm)
Carbon dioxyde	3000	3500
Ammonia	20	50

3. THE OPTIMAL CONTROL PROBLEM

System knowledge as well as control objectives are fundamental to control system design. An optimal control problem is determined by a mathematical model representing the system knowledge and a criterion representing the control objectives. The mathematical model describes the system behaviour as determined by the control and external conditions, and preferably is based on accurate scientific knowledge. The model is represented in the following general form consisting of first-order differential equations,

$$\dot{x} = f(x,u,d,t),\ x(t_0) = x_0 \qquad (1)$$

where x is a vector of state variables, u is a vector of control variables, d is a vector of external variables, t represents time and t_0 the initial time of the optimisation. The initial state x_0 is assumed to be known. For RHOC purposes the dimension 33 of this model was kept as low as possible without compromising to much on its accuracy.

In our case the model describes the influence of the outside weather conditions, i.e. the external variables, and the valve openings, i.e. the control, on the indoor climate conditions, i.e. the state variables, being the relative humidity (RH), temperature (T) and carbon dioxide concentration (CO_2) in the barn. The outside weather conditions are outside temperature, humidity and carbon dioxide concentration, wind direction and wind speed. So the model describes transport phenomena through the walls and valves of the barn. To do this accurately the walls, floor and roof are divided into several layers, each layer being represented by a single temperature node. Within material layers heat storage in temperature nodes and heat transport through conduction between temperature nodes are described. Between the surface temperature nodes, the energy transport through long wave radiation is described. Further the surface nodes deal with energy transport through convection and through condensation and evaporation processes. The temperatures of the construction bounded nodes are additional state variables. The barn is assumed to be perfectly mixed (Ooster, 1994). This is a reasonable assumption in this pilot study, that allows direct comparison of climate parameters and comfort parameters. As a result the model consists of heat and moisture balances and a mass balance of carbon dioxide. The natural ventilation process is computed by a set of routines solving thermal buoyancy and wind effects. The total ventilation rate can be calculated, but also the ventilation rate through groups of valve openings or individual valve openings (Ooster, 1994). The model was originally developed using a finite-element package. To apply optimal control it was translated to the general form of equation (1) (Timmerman, 1999). For a detailed description of the model we refer to (Ooster, 1994). The state variables of the model are the temperatures of all nodes including the air nodes the humidity and carbon dioxide concentration of the barn.

The criterion describes the controller design objectives. The general form of the criterion is,

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

where J is the performance index to be minimised by the control, $\phi(x(t_f),t_f)$ is a weighing function at the final time t_f of the optimisation, $x(t_f)$ is the final state, t_0 is the initial time of the optimisation and L(x,u,d,t) is a weighing function for optimisation over $[t_0, t_f]$. In our case ϕ is not used. J describes the desire to satisfy the comfort parameters, i.e. to keep temperature, humidity and carbon dioxide concentration within pre-specified bounds and preferably at a desired level over $[t_0, t_f]$. Furthermore it describes the desire to keep the airspeed in the valves above a lower bound and preferably at a desired level. Finally it describes the desire to keep the inlet flow through valves at a desired level during normal operation of the barn and at a maximum level during special health endangering operations like manure mixing in cellars. This results in the following criterion,

$$J = \int_{t_0}^{t_f} \begin{pmatrix} q_1 & q_2 & q_3 & q_4 & q_5 & q_6 \end{pmatrix} \times \begin{pmatrix} L_{\Delta t} & L_{RH} & L_{CO_2} & L_n & L_{Deb} & L_{MaxDeb} \end{pmatrix}^T dt \qquad (3)$$

where q_i, i=0,1,..,6 are parameter equal to zero or one and used to switch on and off several parts of the control objectives. Furthermore,

$$L_{\Delta t} = W_{\Delta t}\left(\Delta t - \Delta t_{ref}\right)^2 + W_{\Delta t,high}\left(\Delta t - \Delta t_{high}\right)^2 + W_{\Delta t,low}\left(\Delta t - \Delta t_{low}\right)^2 \qquad (4)$$

$$L_{RV} = W_{RH}\left(RH - RH_{ref}\right)^2 + W_{RH,high}\left(RH - RH_{high}\right)^2 + W_{RH,low}\left(RH - RH_{low}\right)^2 \qquad (5)$$

$$L_{CO_2} = W_{CO_2}\left(CO_2 - CO_{2,ref}\right)^2 + W_{CO_2,high}\left(CO_2 - CO_{2,high}\right)^2 \qquad (6)$$

$$L_v = \sum_{i=1}^{i=4}\left(W_v\left(v_i - v_{ref}\right)^2 + W_{v,low}\left(v_i - v_{low}\right)^2\right) \qquad (7)$$

$$L_{Deb} = W_{Deb}\sum_{i=1}^{i=4}\left(\left(fv_{ref} - fv_i\right)^2\right) \qquad (8)$$

$$L_{MaxDeb} = -W_{MaxDeb}\left(\sum_{i=1}^{i=4} fv_i\right)^2 \qquad (9)$$

are all penalty functions with weighing factors W. The numerical values for the weighing factors result from normalisation of the variables and from scale factors indicating the relative importance of setpoints and bounds. In equations (4)-(7), RH is the relative humidity inside the barn, CO_2 the CO_2 concentration inside the barn, and

$$\Delta t = T - T_{outside} \qquad (10)$$

where T is the air temperature inside the barn and $T_{outside}$ the outside air temperature. Upper bounds for e.g. RH are indicated by the subscript high and lower bounds by the subscript low. The associated weighing factors e.g. $W_{RH,high}$ are zero when the associated bound is not violated otherwise they have a positive value. The subscript ref stands for reference values, i.e. values that should be ideally met. To simplify the problem only four separately controllable valve openings are distinguished in the model, two on each long side of the barn. n_i, $i = 1,2,3,4$ in (7) represent the air speed through each of those. They are a function of the valve openings, i.e. the control, and the outside wind speed and direction, on each side of the barn. The air speeds all have the same reference value n_{ref} and lower bound n_{low}. In equation (8) fn_i, $i = 1,2,3,4$ represent the air flows through the valves and the equation describes the desire to supply a sufficient amount of fresh air for the need of the animals and to realise a sufficient distribution of the incoming air. Equation (9) represents the desire to get maximal airflow during special operations in the barn. Also the ridge is open, but this opening is not considered as a controllable opening.

4. RECEDING HORIZON OPTIMAL CONTROL

Because the model is not a perfect description of the system and due to inaccuracies and uncertainty regarding the initial state and the external variables, application of the optimal control alone will not result in an optimal system performance. To properly deal with these inaccuracies and uncertainty feedback is required, i.e. from on-line measurements the actual system behaviour is estimated and the control is adjusted accordingly. Receding horizon optimal controllers at each sampling instant t_i, i=0,1,.., $t_{i+1} > t_i$ estimate the state $x(t_{i+1})$ from the past measurements $y(t_i)$, $y(t_{i-1})$, $y(t_{i-2})$, .. .This estimate $\hat{x}(t_{i+1})$ is used as the initial state of an optimal control problem over the time interval $[t_{i+1}, t_{i+N}]$. This optimal control problem is solved inside the time-interval $[t_i, t_{i+1})$ resulting in an optimal control sequence $u(t_{i+1})$, $u(t_{i+2})$,.., $u(t_{i+N})$. Of this control only the first value $u(t_{i+1})$ is applied to the system at time t_{i+1} and then the procedure is repeated. So at every sampling instant receding horizon controllers adjust the control to deviations caused by inaccuracies and uncertainty of the model, the initial state and the external variables. As opposed to other controllers the adjustment is made in an optimal manner. The length of the time interval $[t_{i+1}, t_{i+N}]$ i.e. $t_{i+N}-t_{i+1}$ is called the optimisation horizon of the RHOC.

Important issues in RHOC design are the choice of the horizon length and the translation of the control objectives over the full control horizon to control objectives over the limited optimisation horizon $[t_{i+1}, t_{i+N}]$ of the RHOC. A too small optimisation horizon results in loss of performance since future behaviour is disregarded. A too large optimisation horizon also leads to a loss of performance due to the increasing uncertainty in future behaviour which is used to compute the control. As in greenhouse climate control, in our case the outside weather conditions heavily influence the system behaviour. Tap *et al.* (1996) demonstrated that the use of the so called 'lazy man weather prediction' is to be preferred over the use of other available weather predictions, in the design of a receding horizon optimal greenhouse climate controller. They computed an optimal length of the optimisation horizon of one hour. Since our climate control problem has many characteristics in common with greenhouse climate control our simulation results are also computed with an optimisation horizon of one hour. Clearly the choice of the optimisation horizon needs to be investigated further similar to the investigation presented by Tap *et al.* (1996). The implementation of the receding horizon controller is based on an algorithm proposed by Van Willigenburg (1995). This algorithm enables the choice of arbitrary sampling periods, while taking explicitly into account the continuous-time inter-sample behaviour. Note that a RHOC supplies only the initial values of the optimal control to the system at each sampling instant. By enlarging the first sampling period in the optimal control computation, the relative importance of the initial values of the control is increased. Without manipulating the criterion this phenomenon may be exploited to circumvent the problem of low sensitivity of the optimal control problem to the initial values of the control. This low sensitivity may result in poor initial values of the control and hence decrease the performance of RHOC.

5. RESULTS

To demonstrate the high potential of a RHOC to automatically control the ventilation and the associated climate in cattle barns the results of two simulations, with different control objectives, are presented in this section. Furthermore two other simulations were performed to compute the loss of performance caused by the imperfect 'lazy man weather prediction' as compared to perfect weather prediction which in practice is infeasible. Given the similarities with greenhouse climate control the optimisation horizon t_{i+N}-t_{i+1} is set to one hour (Tap *et al.* ,1996). The rate at which the control is updated was three minutes. The sampling interval of the control computations over the control horizon was taken to be twenty minutes. As explained in the previous section by increasing this sampling interval the sensitivity to the initial control can be increased. Clearly the choice of this sampling interval and of the optimisation horizon need further investigation.

In the first simulation the four inlet valves on both sides of the barn could be controlled between openings of 1 and 24,5 cm. The active control objectives were temperature difference, relative humidity and CO_2-concentration. This is realised by taking (q_1 q_2 q_3 q_4 q_5 q_6) = (1 1 1 0 0 0) in equation (3). The reference values in (4)-(6) are,

temperature difference:
$Dt_{ref} = 3\ ^{o}C$, $Dt_{high} = 5\ ^{o}C$, $Dt_{low} = 2\ ^{o}C$
relative humidity (CIGR, 1984):
$RH_{ref} = 0{,}5*(RH_{high} + RH_{low})$ %,
$RH_{high} = 95$ % when $t_i < -5\ ^{o}C$ otherwise:
$RH_{high} = (90 - t_i)$ %
$RH_{low} = 50$ % when $t_i < 20\ ^{o}C$ otherwise:
$RH_{low} = (70 - t_i)$%
CO_2-concentration:
$x_{CO2,\ ref} = 2$ g/kg dl, $x_{CO2,\ high} = 3$ g/kg dl.

The weighing factors are,
temperature difference:
$W_{Dt} = 2$, $W_{Dt,\ high} = 20$, $W_{Dt,\ low} = 0$
relative humidity:
$W_{RH} = 0.08$, $W_{RH,\ high} = 0.8$, $W_{RH,\ low} = 0.8$
CO_2-concentration:

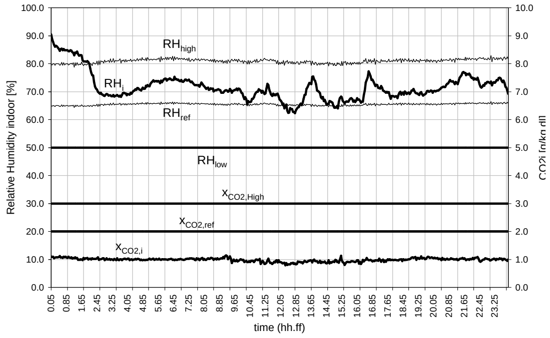

Fig. 3 *Simulation with q= (1 1 1 0 0 0). Internal Relative humidity and carbon dioxide concer tration as a result of the control actions with indicaton of the criterion limits.*

$W_{CO2} = 0$, $W_{CO2,\ high} = 2000$

The calculated temperature difference stays below the upper bound and close to the reference value during most of the day, see figure (1). At only one instant during the day temperature difference exceeds the upper bound. This is caused by a sudden drop in wind speed and outside temperature, see figure (2).

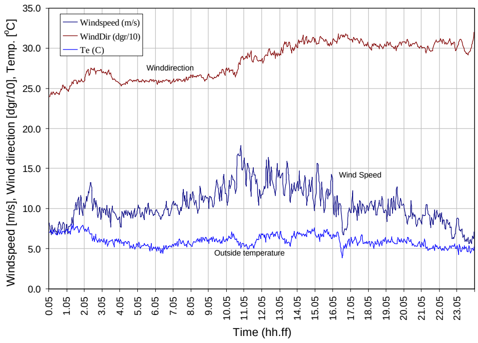

Fig. 2 *Measured wind speed and wind direction during first simulation (19-February* 1993)

Except for the first couple of hours the calculated relative humidity stays below the upper bound and stays close enough to the reference value, that is between the upper and lower bound (figure 3). In the first hours it was not possible to keep the relative humidity below the upper bound due to a high outside relative humidity.

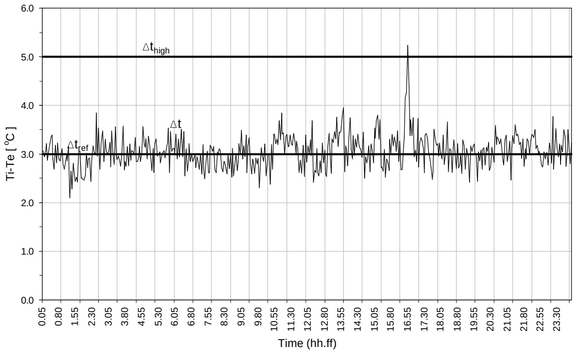

Fig. 1 *Simulation with q= (1 1 1 0 0 0). Temperature difference as a result of the control actions.*

The course in time of the relative humidity can be explained by the course in time of the outside temperature and outside relative humidity (figure 2 and figure 3). The CO_2-concentration is very stable and stays far below the upper bound. In summary a good climate is realised during most of the day.

To obtain insight in the loss of performance due to the receding horizon of 1 hour a full optimisation was performed over the whole day using the same weather data. When the weather is more variable during the day the loss of performance is expected to be larger. Although the weather used in the optimisation had a large variability the loss of performance was only 5 percent.

In the second simulation the four inlet valves on both sides of the barn could again be controlled between openings of 1 and 24,5 cm. The control objectives were the air flow and air speed through the valves. To realise this (q_1 q_2 q_3 q_4 q_5 q_6) = (0 0 0 1 1 0) was selected in equation (3). Furthermore the reference values, bounds and weighing factors in (7)-(9) were chosen as follows,

air speed:

v_{ref}= 2 m/s, v_{low}= 1,5 m/s, W_v= 100, $W_{v,\,low}$= 10000,

air flow:

fv_{ref}= 4,24*r_e kg (dry air)/s per inlet valve,

W_{deb} = 20000

The desired air flow through the valves fv_{ref} is calculated from the advised ventilation per animal per hour in mechanically ventilated dairy barns (IKC, 1993). The desired total air flow for the total occupation of the test barn is 61015 m^3/h (= 16,95 m^3/s). This air flow will be evenly divided among the four valves, which equals 4,24 m^3/s for each valve. To sufficiently mix the incoming fresh air with the air inside the barn the lower bound for the air speed is 1,5 m/s.

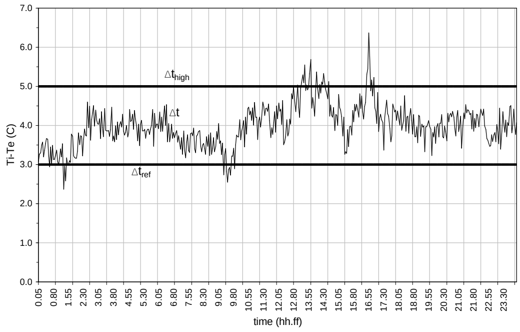

Fig. 4 *Simulation with q= (0 0 0 1 1 0). Realised temperature difference between indoor air and outdoor air.*

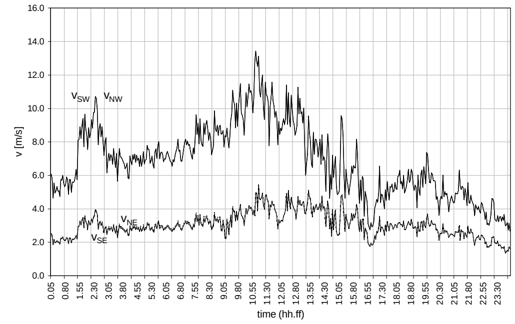

Fig. 6 *Simulation with q= (0 0 0 1 1 0). Realised air velocity in the controlled ventilation valves at eaves height of the building.*

The temperature difference and the CO_2-concentration are higher than those in the previous simulation because the total air flow is lower in this case (figure 4 and figure 5). This reduces heat losses and CO_2-losses through ventilation. A higher reference value for the air flow results in a smaller temperature difference and lower CO_2-concentration. The course of the relative humidity is almost identical to the one in the previous simulation.

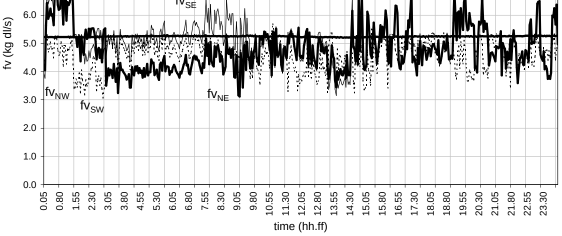

Fig.7 *Simulation with q= (0 0 0 1 1 0). Realised airflow in kg dry air /sec through the controlled ventilation valves at eaves height of the building.*

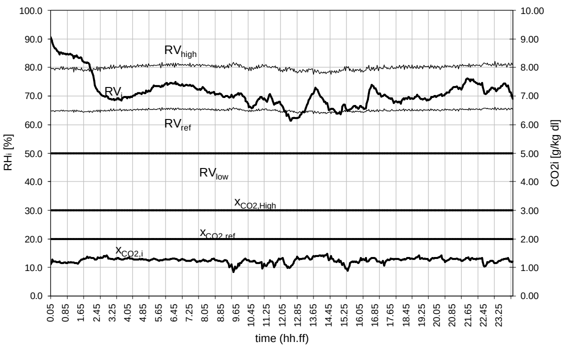

Fig. 5 *Simulation with q= (0 0 0 1 1 0). Realised relative humidity and carbon dioxide concentration in the indoor air.*

All four valves are partly opened during the whole of the day. From figure (6) it is clear that the calculated air speed in the valves stays above the lower bound. The air flow through the valves are almost evenly divided among the valves and are close to the reference value (figure 7). The control objectives are met and a good climate is realised during most of the day.

In both simulations the course of the valve openings (figure 8 and 9) is very dependent on wind speed and wind direction indicating the well known fact that the natural ventilation process depends heavily on wind speed and wind direction.

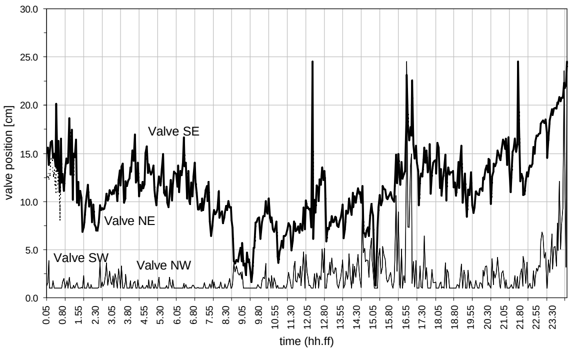

Fig. 8 *Simulation with q= (1 1 1 0 0 0). Valve positions as they are set by the RHOC.*

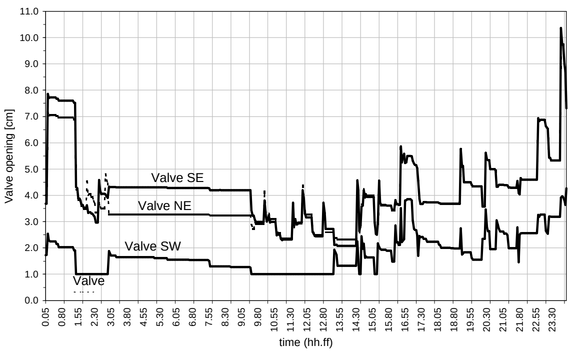

Fig. 9 *Simulation with q= (0 0 0 1 1 0). Valve positions as they are set by the RHOC.*

6. CONCLUSIONS

The design and simulation results of a digital optimal receding horizon controller for the control of the climate in cattle barns through ventilation have been presented. As to the design the optimal control approach enables to fully exploit scientific knowledge concerning the behaviour of the climate variables in and outside the barn to control the ventilation. This knowledge was captured in a high dimensional model. The optimal control approach requires an exact formulation of the control objectives, which may be conflicting, as they sometimes are in this application. In these cases an optimal compromise is obtained. As explained in this paper the optimal receding horizon control algorithm explicitly considers the inter-sample behaviour. This makes it possible to circumvent practical problems associated to the possible low sensitivity to the initial value of the control, which is the only one actually applied to the system by a receding horizon controller. By extending the sampling interval in the receding horizon control computation the sensitivity to the initial control increases. Finally the extension of the (initial) sampling interval very well suits the use of the so called 'lazy man weather prediction' which seems the best sort of weather predictions available for this application.

The simulations reveal that the approach is very promising since if possible, the climate stays within the pre-specified climate ranges, and if not possible, an optimal compromise is realised between conflicting interests. Of course the successful applicability in practice depends also on the accuracy of the model describing the climate behaviour inside and outside the barn. With respect to this note that a receding horizon optimal controller is very well suited for on-line adaptation of model parameters. By means of the scaling factors that are part of the weighing factors, the user of the controller can personalise the relative importance of cost function components. Sensitivity analysis is still needed to set logical ranges for these scale factors. A practical problem that has to be solved is the estimation of the state, which in simulation was assumed to be equal to the simulated state. Both the accuracy and possible improvement of the model and the estimation of the state will be subjects of future research. The system is ready for prototyping in lab tests and in practise.

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