Model Predictive Control (MPC) of hybrid ventilation systems in office buildings with dynamic glass facades

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ABSTRACT

An advanced heat and electricity saving strategy for the regulation of hybrid ventilation systems with automatic night cooling (ventilative cooling), mechanical compressor cooling, natural ventilation and exterior solar shading by the inclusion of MPC (Model Predictive Control) has been developed in this project. The focus is on the optimization of the total energy cost (cost function) as compared to indoor climate requirements and variations in the outdoor climate. During the test period, the test persons could override the automatic control of the natural ventilation and solar shading. Their experience with the control strategy was studied by anthropologists.

KEYWORDS

Ventilative cooling, model predictive control MPC, natural ventilation

1 INTRODUCTION

The objective of predictive control (MPC) is to coordinate the use of mechanical ventilation, solar shading, window opening, heating and cooling coils to achieve room temperature and CO_2 containment within recommended limits on the cost in the cheapest way. It is used fixed energy prices any time of the day and focus hereby to achieve the lowest possible energy consumption. It is simple to use varying price forecasts and thus involve the availability of power across a predictive horizon. The predictive control coordinates the use of the above actuators using a dynamic model for the office, and is every half hour updated with the latest measurements of temperature and CO2 as well as the latest forecasts of outdoor temperature, solar intensity and person load. From this calculates an optimized of the predictive control how the actuators set every half hour in a given time frame, for example 24 hours, the cheapest way to meet comfort requirements. In the example, calculates the predictive control every half hour a cycle of 48 signals for each actuator, that is, 5x48 values. The idea of

predictive control is that only the first set of 5 values used in the controller, after half an hour corrected in subsequent values in a new optimization. For predicting outside temperature and solar intensity envisaged point forecasts from DMI which can deliver forecasts for every hour 54 hours until 4 times a day in a 3x3 km grid.
To illustrate the operation is made two types of simulations: one where constructed course outside temperature, solar intensity and person load in a winter scenario, a summer scenario and a transition scenario; in the other type is used DRY measured data for one year. In most simulations it is assumed that the model describes the real office sufficient and that the real temperatures of the process, etc. consistent with forecasts. This gives a picture of what the predictive control at best can achieve.

2 MODEL

If the calculations have to be very accurate, needs to be developed a large number of equations, in principle, one for each temperature of surfaces and thin layers of the heat-accumulating parts are desired; As mentioned, however, in many cases doubtful whether this trouble worthwhile. Here is, therefore, sought the greatest possible simplification with only 3 equations for each time interval.

Room air heat balance

$$\Sigma\alpha\cdot A\cdot(t_o - t_{air}) = \mathbf{B_o}\cdot(t_o - t_{air}) \tag{1}$$

Where:
α is convective heat transfer for floors 2,5 $W/(m^2\cdot{}^oC)$, 2,0 $W/(m^2\cdot{}^oC)$ for ceilings and 3,0 $W/(m^2\cdot{}^oC)$ for walls
A is surface area, m^2
t_o is surface temperature, ${}^oC$
t_{air} is room air temperature, ${}^oC$

$$G\cdot c_p\cdot(t_{air} - t_i) = \mathbf{B_l}\cdot(t_{air} - t_i) \tag{2}$$

where:
G is the airflow (natural or mechanical), kg/s
c_p is heat capacity of air, $W/(kg\cdot{}^oC)$
t_i is the inlet air temperature, ${}^oC$

$$Q_{conv} + \mathbf{B_o}\cdot(t_o - t_{air}) = \mathbf{B_l}\cdot(t_{air} - t_i) \tag{3}$$

Where:
Q_{conv} is convective heat to the room, W

Room surface heat balance

$$\Sigma k\cdot A = \mathbf{B_u} \tag{4}$$
$$\Sigma k\cdot A = \mathbf{B_r} \tag{5}$$

Where:
(4) is heat transfer from surface to out side
(5) is heat transfer from surface to neighbor room

$$\Sigma k'_a\cdot A = \mathbf{B_a} \tag{6}$$

Where:
(6) is heat transfer from surface to fictive accumulative layer in the wall

$$Q_{rad} = \mathbf{B_u}\cdot(t_o - t_u) + \mathbf{B_r}\cdot(t_o - t_r) + \mathbf{B_o}\cdot(t_o - t_{air}) + \mathbf{B_a}\cdot(t_o - t_a) \qquad (7)$$

Where:
Q_{rad} is heat by radiation, W
t_a is temperature in fictive accumulated layer, ^oC

Fictive accumulative wall layer heat balance

$$\Sigma c_p\cdot\varrho\cdot A\cdot e\cdot\frac{\partial t_a}{\partial \tau} = \boldsymbol{S}\cdot\frac{\partial t_a}{\partial \tau} \qquad (8)$$

Where:
S is the rooms heat capacitive, J/^{o}C
c_p is heat capacitive, W/(kg·^{o}C)
ϱ is density, kg/m^3
A is surface, m^2
e is thickness of fictive accumulative layer, m

$$\mathbf{B_a}\cdot(t_o - t_a) = \mathbf{S}\cdot\frac{\partial t_a}{\partial \tau} \qquad (9)$$

The differential equation (9) must be changed to a difference equation to be processed manually. Divided the analysis time in intervals of length Δτ applies to the n'th interval:

$$\mathbf{B_a}\cdot(t_{o,n-1} - t_{a,n-1}) = \mathbf{S}\cdot\frac{t_{a,n} - t_{a,n-1}}{\Delta\tau} \qquad (10)$$
$$Q_{conv,n} + \mathbf{B_o}\cdot(t_{o,n} - t_{air,n}) = \mathbf{B_l}\cdot(t_{air,n} - t_{i,n}) \qquad (11)$$
$$Q_{rad,n} = \mathbf{B_u}\cdot(t_{o,n} - t_{u,n}) + \mathbf{B_r}\cdot(t_{o,n} - t_{r,n}) + \mathbf{B_o}\cdot(t_{o,n} - t_{air,n}) + \mathbf{B_a}\cdot(t_{o,n} - t_{a,n}) \qquad (12)$$

Summary – room simulation model

Input: $\mathbf{B_a}$**,** $\mathbf{B_l}$**,** $\mathbf{B_o}$**,** $\mathbf{B_r}$**,** $\mathbf{B_u}$**, S,** Q_{conv}, Q_{rad}, t_u, t_i, t_r
Output: t_{air}, t_o, t_a

2.1 Cost function

Electric power to the fans is given partly by an empirical model for the power consumption

$$P_{ventilatorer} = \left(\frac{q_l}{q_{max}}\right)^{2.5}\cdot q_{max}\cdot SEL_{\max}\ [Watt] \qquad (13)$$

Where:
q_{max} is the maximum air flow, m^3/s
q_l is the actually air flow, m^3/s
SEL_{max} is the specific fan power at q_{max}, J/m^3. It is 2100 J/m^3 in Denmark

$$P_{cooling\ coil} = COP\cdot P_{el\text{-}compressor} \qquad (14)$$

Where
COP is the compressor cooling factor. It has the value 3,0

$P_{heating} = q_l \cdot \varrho \cdot c_p \cdot (t_i - t_{air})$ (15)

$P_{heating\ coil} = q_l \cdot \varrho \cdot c_p \cdot (t_i - t_u')$ (16)

Where:
t_u' is equal to $(t_u + \eta \cdot (t_{air} - t_u))$ (17)
η is the heat recovery value. In Denmark it is 0,70

$P_{heating\text{-}radiator}$ = desirable heat

Electricity price = 2,25 Dkr/kWh
Heating price = 0,75 Dkr/kWh

It is assumed that the cost of solar protection is negligible. In MPC routine, we have chosen to put a very small price of solar protection as a simple way to avoid foreclosure remains active for periods where there is no need for it.

In view of the mentioned costs we can now establish a cost function V, which is the price of comply comfort within a given time frame as a function of the use of the various actuators, ventilation (q_l), heating ($P_{heating}$), cooling ($P_{cooling}$), solar shading and window opening.

$$V\left(q_l, P_{heating}, P_{cooling}\right) = \sum_{k=1}^{N} hP_{ventilatorer}(k)El\_price + hP_{heating}(k)Heat\_price + \frac{hP_{cooling}(k)Heat\_price}{COP} + (b_s(k) - 1)^2 Solar\_shading \qquad (18)$$

N is here the time horizon, h is the time resolution.

The cost function to be minimized, taking into account the following limitations given by comfort and actuators extremes:

Indoor temperature, T_{air}, determined from room temperature dynamics with the conditions in terms of climate and space use.
CO_2 concentration determined from room.
$T_{min} \leq T_{air} \leq T_{max}$ where $T_{min\text{-}summer} = 23\ ^oC$, $T_{min\text{-}winter} = 20\ ^oC$, $T_{max\text{-}summer} = 26\ ^oC$ and $T_{max\text{-}winter} = 24\ ^oC$
$CO_{2\ max} = 1000$ ppm
$0 \leq q_l \leq q_{max}$, where $q_{max} = 250\ m^3/h$
$P_{heating}$ and $P_{cooling}$ must be positive.
Ventilation through window opening between 0 and maximum window flow, $0 \leq q_{vent\text{-}nat} \leq q_{vent\text{-}nat\text{-}max}$, where $q_{vent\text{-}nat\text{-}max} = 1{,}8$ liter/(s·m^2) floor area.

Indoor Climate Control allows sequences of actuator signals q_l (1) ... q_l (N), $P_{heating}$ (1) ... $P_{heating}$ (N), $P_{cooling}$ (1) ... $P_{cooling}$ (N), bs (1) ... bs (N), $q_{vent\text{-}nat}$ (1) ... $q_{vent\text{-}nat}$ (N) in order to comply with the restrictions. Many combinations of actuator values can comply with the limits. Model Predictive Control (MPC) can calculate the sequence of the actuator with the lowest cost, if it has the correct information in the form of weather predictions, number of people in the room and it has a model that can correctly calculate the inside temperature and CO_2 concentration.

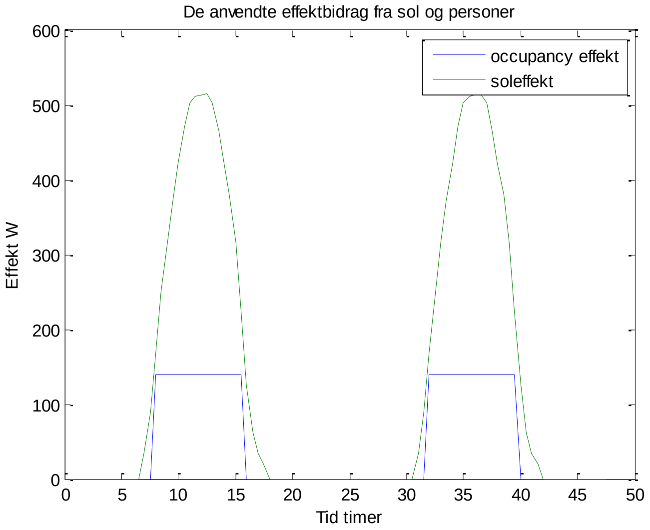
MPC operates so that within a predictive horizon, N, calculated a course of actuators which minimize the cost, then used the first value of the actuator signals.

The room simulation model and the minimum cost function is running in the Matlab environment with CVX included. CVX is a Matlab-based modeling system for convex optimization. CVX turns Matlab into a modeling language, allowing constraints and objectives to be specified using standard Matlab expression syntax.

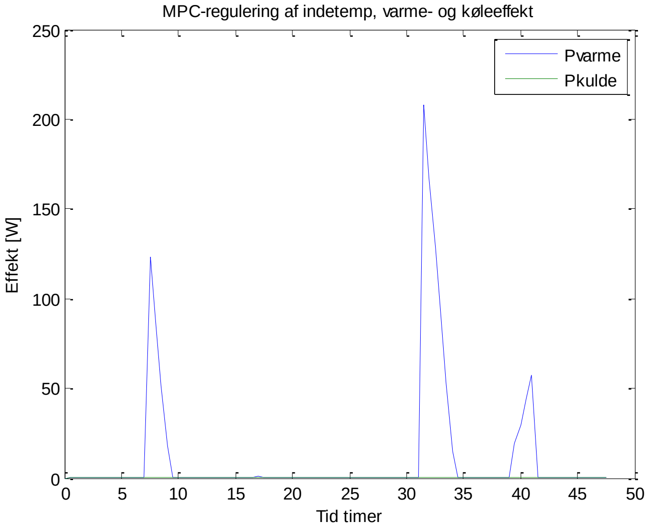
2.2 Results

There is in this paper presented some selected simulation.

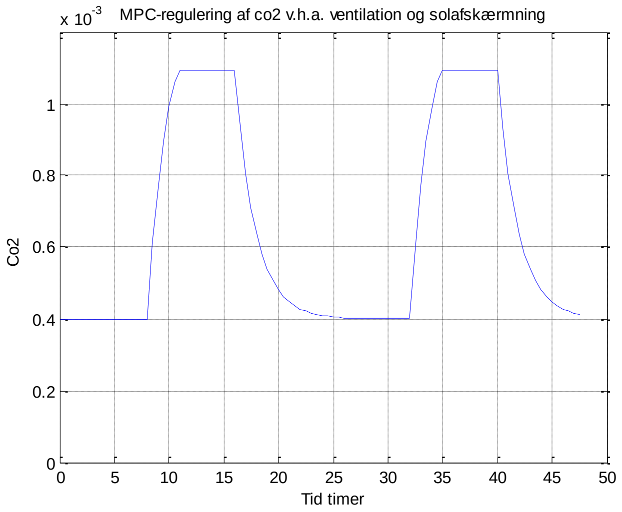
Winter with heating demand:

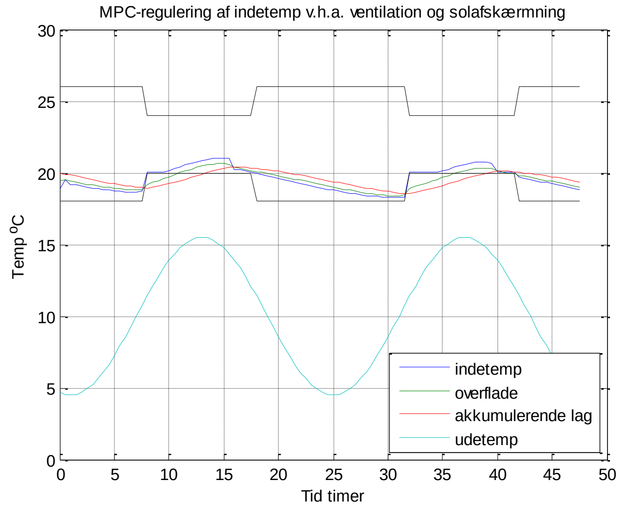


Green line = solar power.

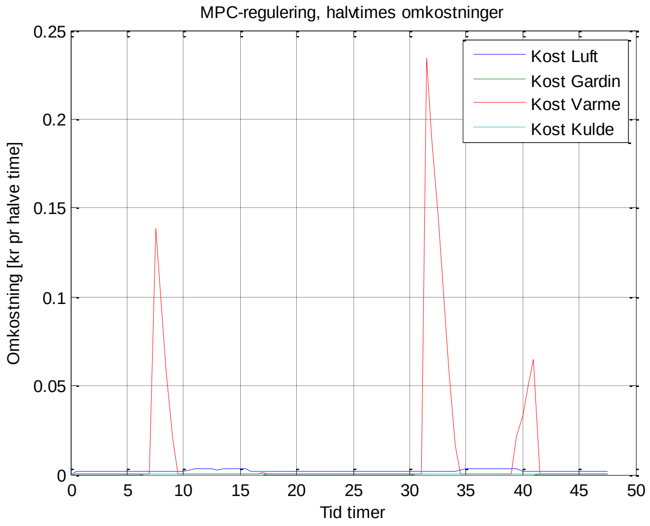


Blue line = $P_{heating}$ *and green line =* $P_{cooling}$



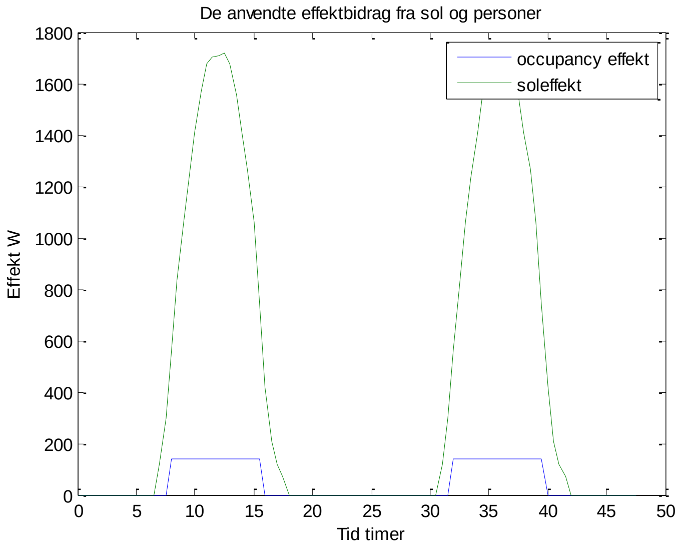


Blue line = t_{air}, green line = t_o, red line = t_a and light blue = t_u

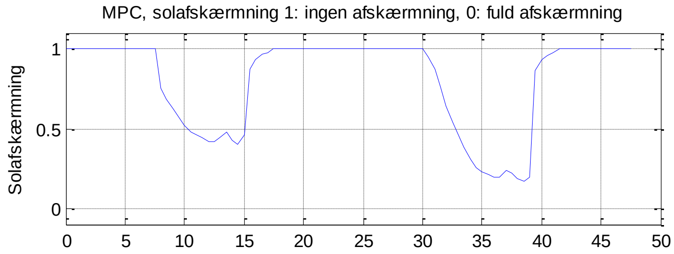


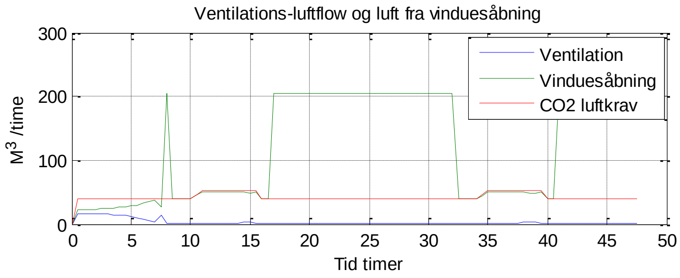
Red line = cost (heating), blue line = cost (ventilation)

Summer:

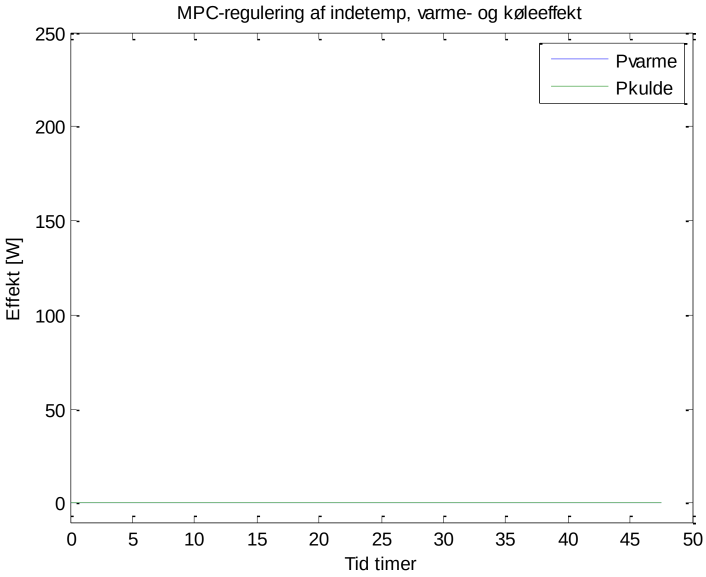


Green line = solar power.

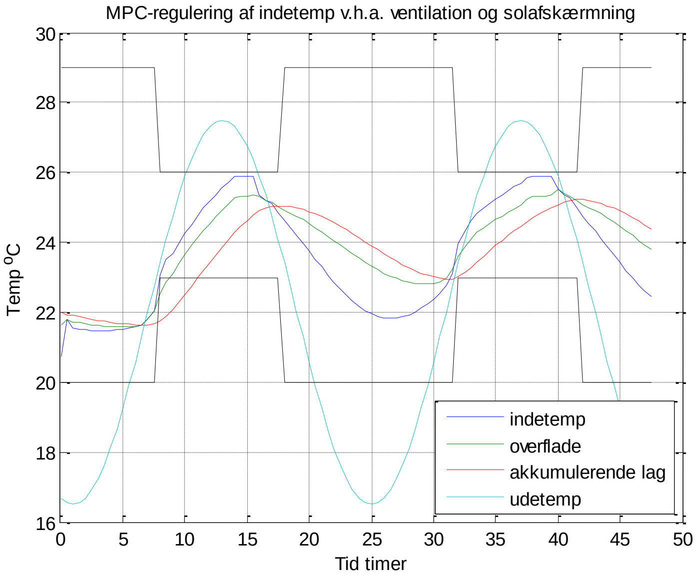




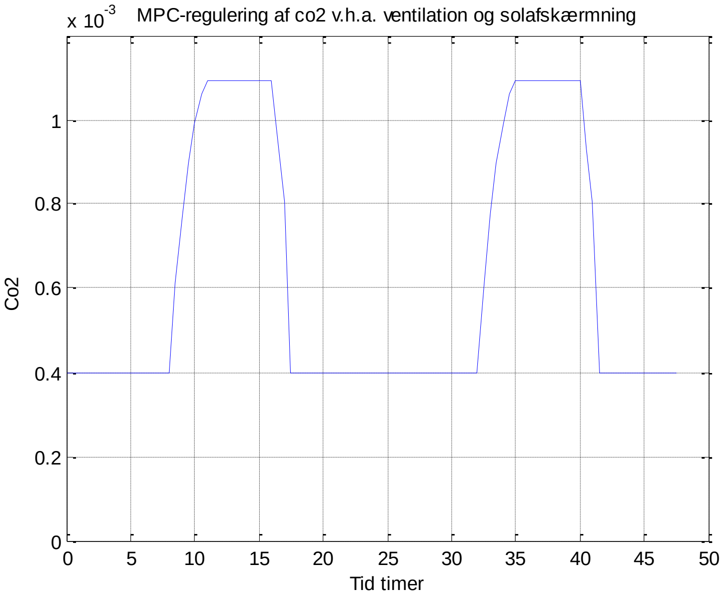
Solar shading. "1" = no shading
Blue line = mechanical ventilation, green line = natural ventilation



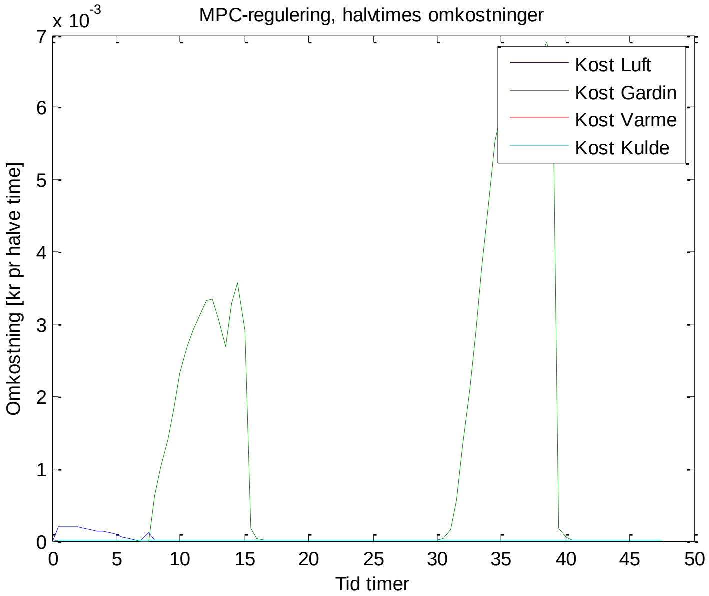
Blue line = $P_{heating}$ *and green line =* $P_{cooling}$



Blue line = t_{air}*, green line =* t_o*, red line =* t_a*, light blue =* t_u



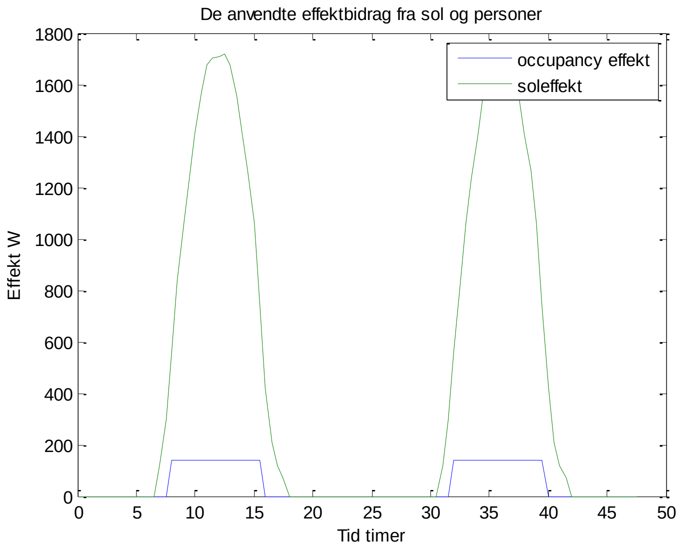
MPC-regulering af co2 v.h.a. ventilation og solafskærmning



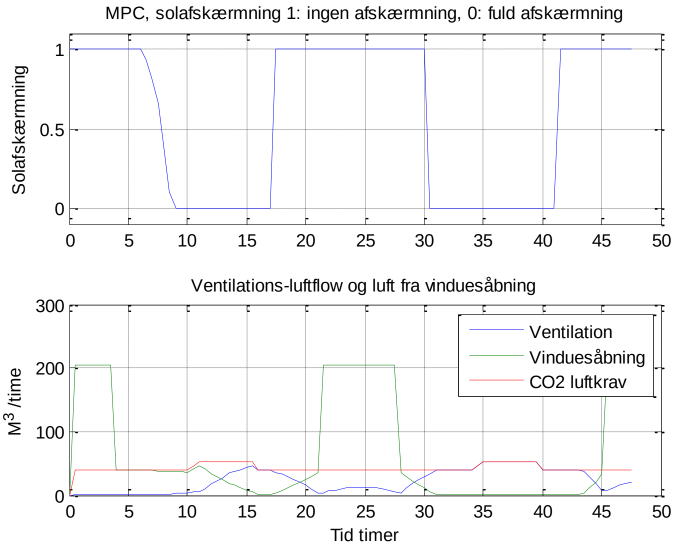
MPC-regulering, halvtimes omkostninger

Green line = ”cost” solar shading, blue line = cost ventilation.

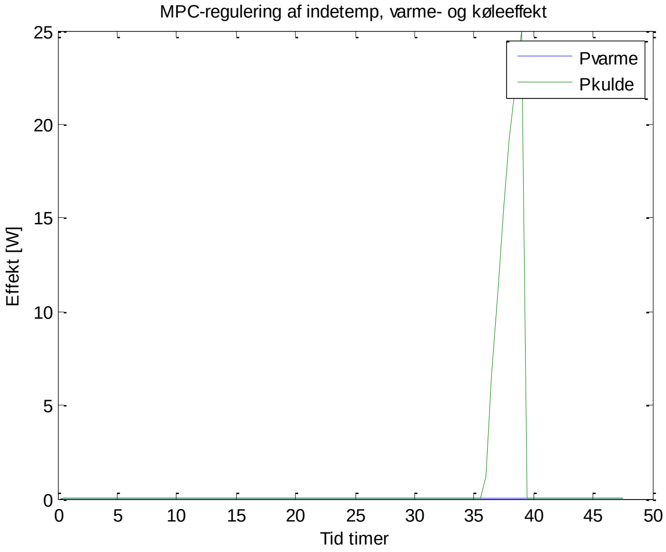
Hot summer:



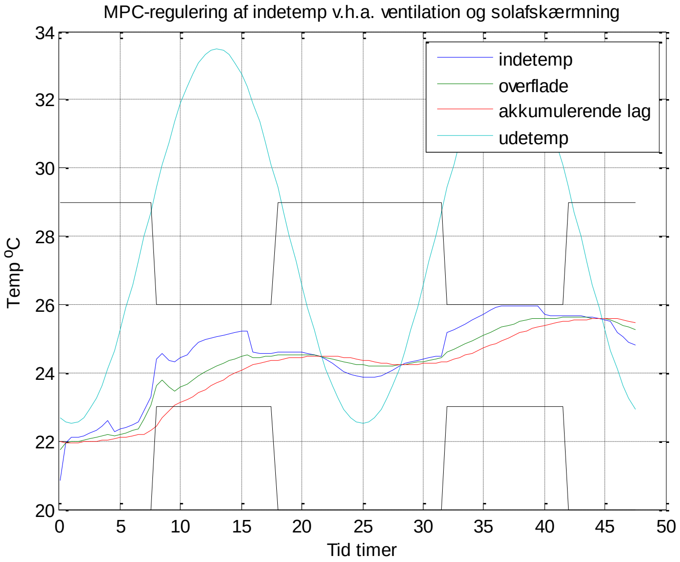
Green line = solar power.



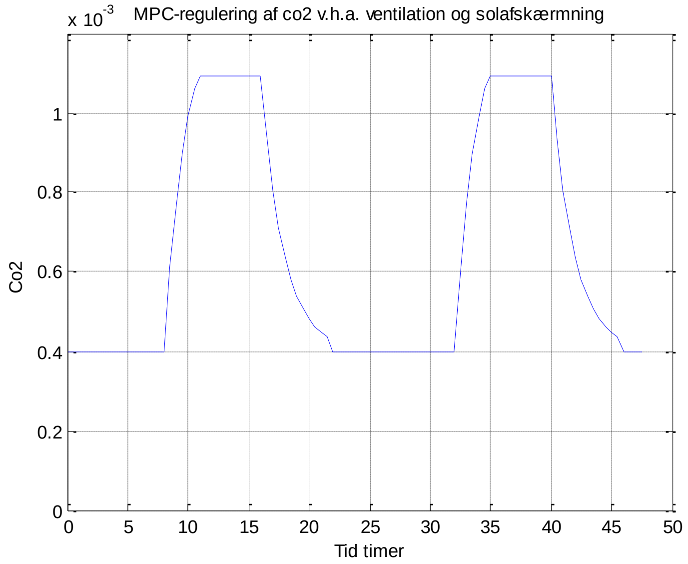
Blue line = solar shading. “1” = no shading.
Blue line = mechanical ventilation, green line = natural ventilation

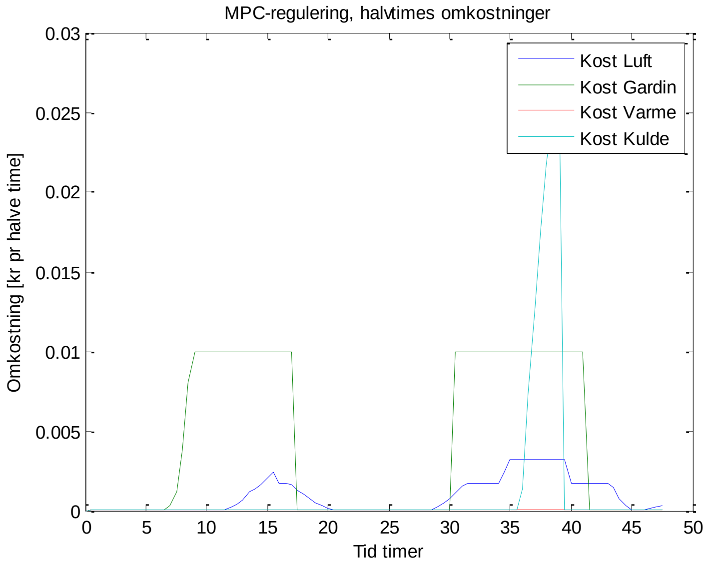


Green line = $P_{cooling}$ and blue line = $P_{heating}$



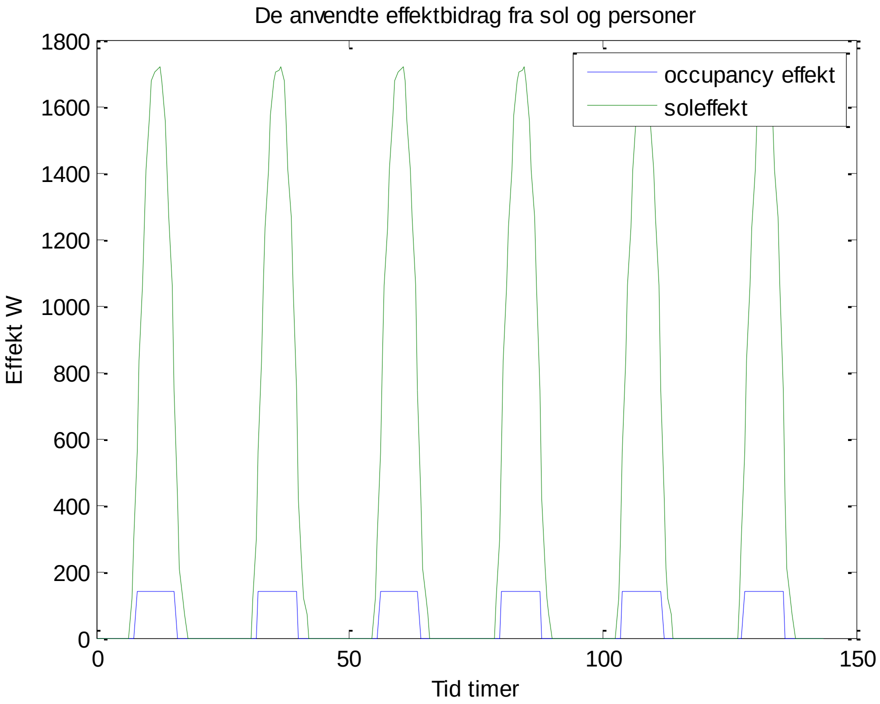
Blue line = t_{air}, green line = t_o, red line = t_a and light blue = t_u



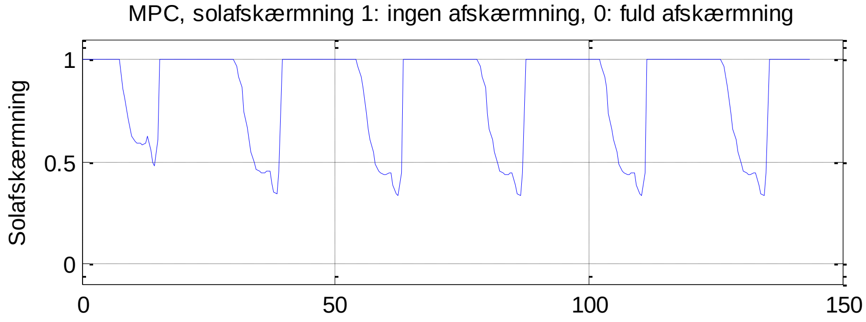


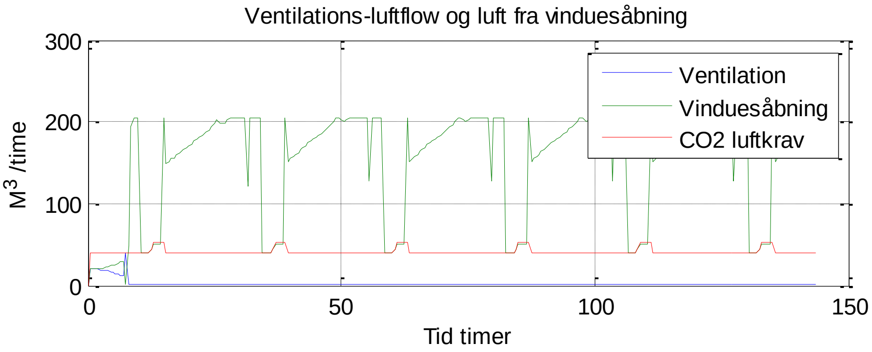
Blue line = cost (ventilation), green line = ”cost” (solar shading), light blue line = cost (cooling)

<u>Summer (long time simulation)</u>

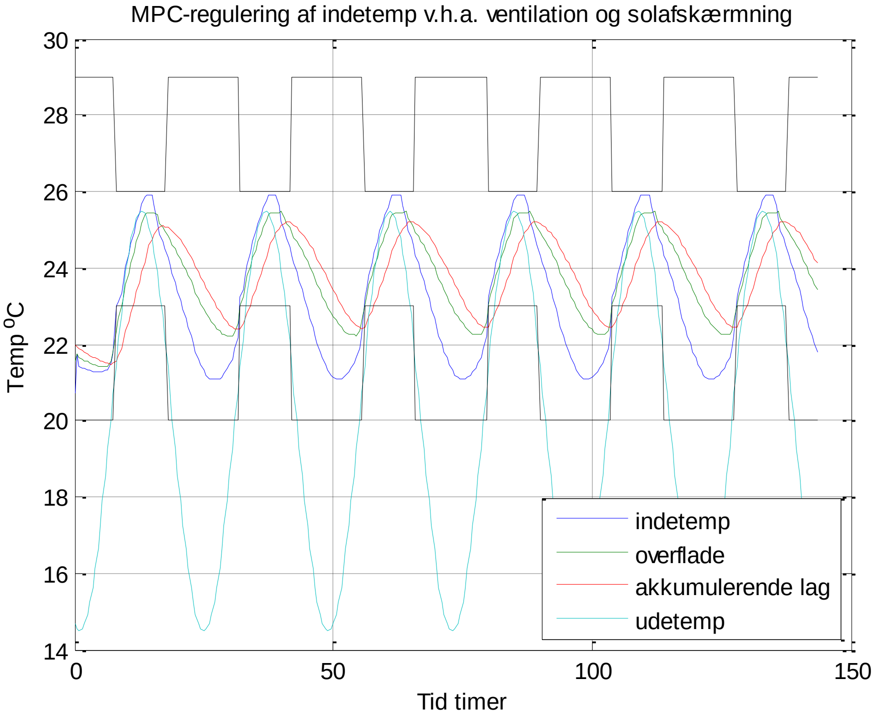


Green line = solar power.

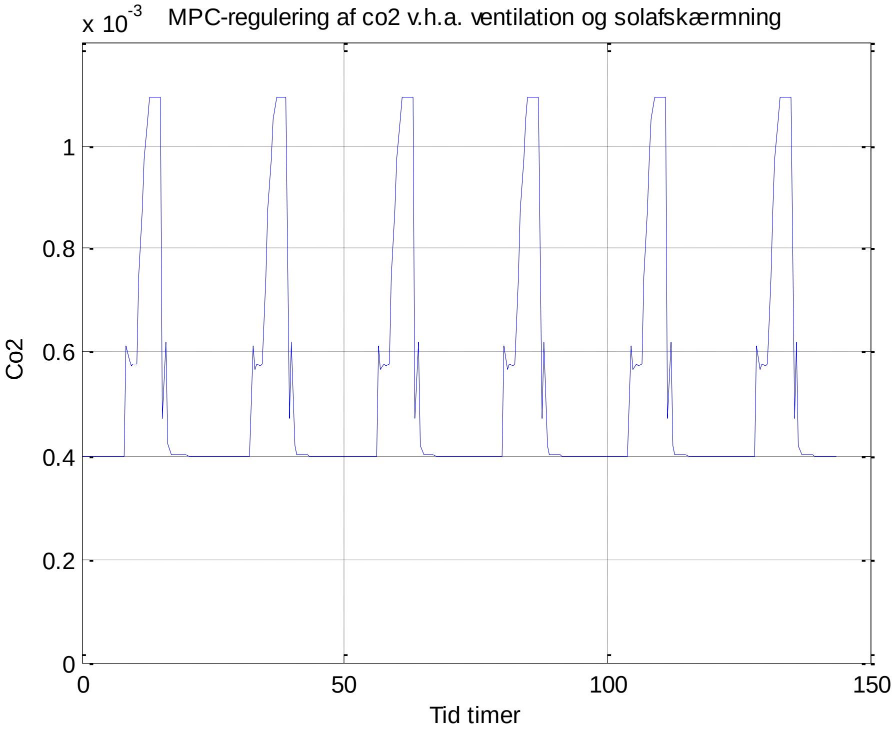


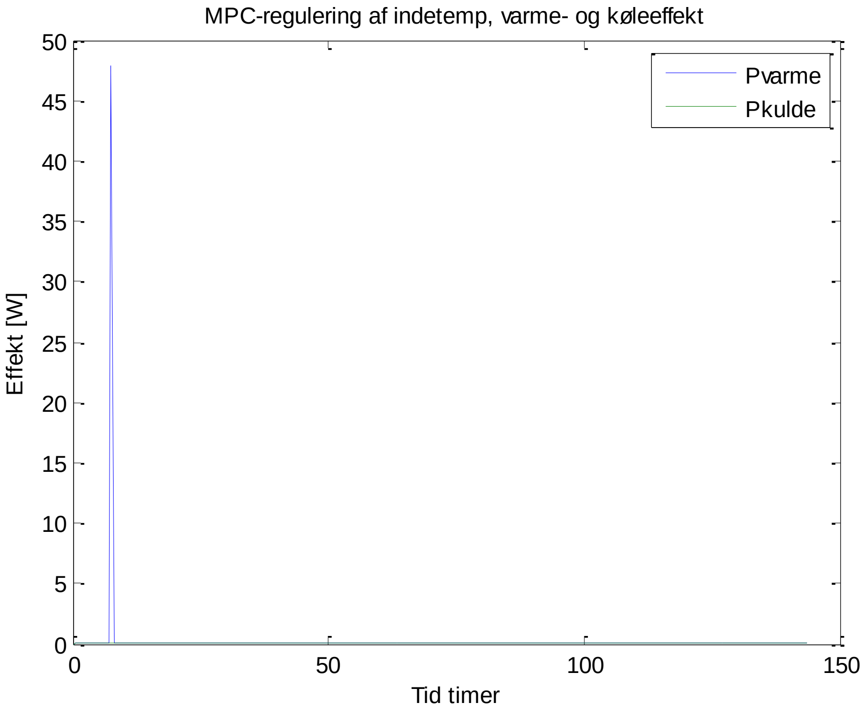


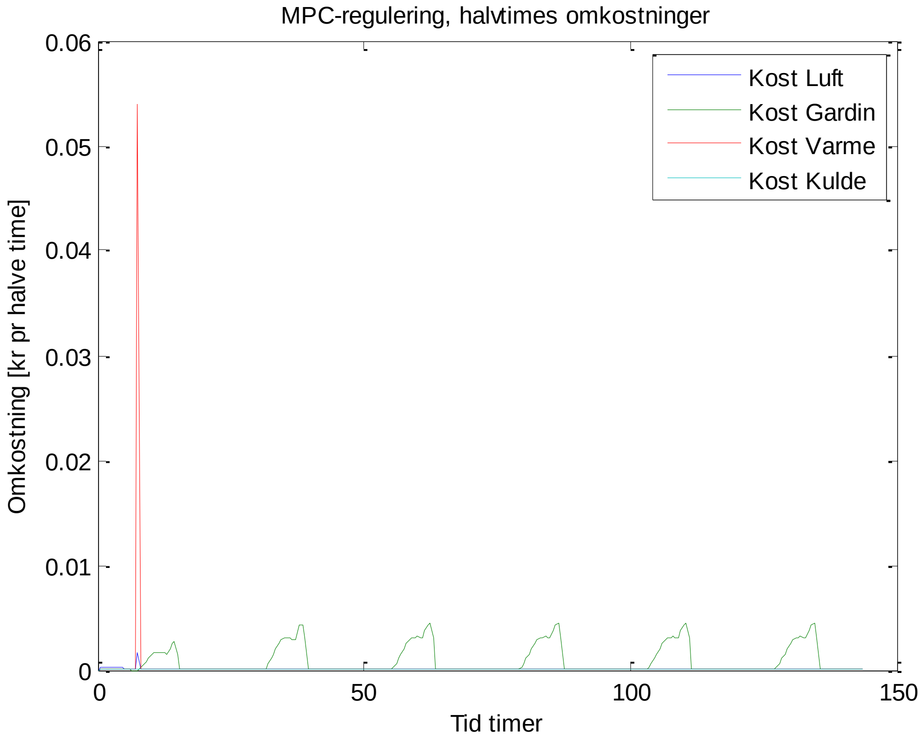
Blue line = solar shading. ”1” = no shading.
Blue line = mechanical ventilation, green line = natural ventilation



Blue line = t_{air}, green line = t_o, red line = t_a and light blue = t_u







Green line = ”cost” solar shading

3 CONCLUSIONS

Using an simple building model, MPC and weather forecast in combination with indoor climate requirements and cost function to control: Mechanical ventilation, natural ventilation, heating, cooling, solar shading in an optimal way. It is not necessary with more than 24 hours weather

forecast. On a normal summer day in Denmark, it was possible to hit a room temperature of 23 degrees C at 8 am and a room temperature of 26 degrees C at 16 without the use of mechanical cooling but only natural ventilation and solar shading.
The advanced control strategy can be optimized more through user feedback.

4 ACKNOWLEDGEMENTS

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