POTENTIAL AND PARAMETER SENSITIVITY OF MODEL BASED PREDICTIVE CONTROL FOR CONCRETE CORE ACTIVATION AND AIR HANDLING UNIT

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ABSTRACT

This paper presents a sensitivity analysis of Model based Predictive Control (MPC) performance, with the final goal to rank the building and system parameters influencing the robustness of the MPC. For a building with Concrete Core Activation (CCA), the potential of MPC is assessed and the parameters (prediction values of ambient temperature, solar radiation and occupancy; measurement accuracy of zone and CCA temperatures; cost function values of the CCA or AHU production units; system constraints such as available thermal power of the production units) are varied within typical uncertainty ranges and the change in control performance is investigated. The resulting parameter ranking serves as a priority list for future improvement of MPC robustness.

INTRODUCTION

Buildings with Concrete Core Activation (CCA) are intrinsically energy efficient buildings. The limited thermal power and the large time constant of CCA force the building envelope to be of high quality. Low heating and high cooling water temperatures enable the use of renewable and energy efficient heat/cold production systems. However, CCA introduces a high thermal mass in the HVAC system, which can have a negative impact on the control performance (Parys, 2012). Conventional CCA control should come down to a continuous operation and keeping the concrete temperature at level (Sourbron and Helsen, 2013a; Olesen, 2000). However, an additional fast reacting system such as the air handling unit can be used to improve controllability and user satisfaction.

In order to control the combination of the slow CCA and the additional fast system, Model based Predictive Control (MPC) is a good candidate to avoid counteractive operation and to optimally deploy both systems to guarantee thermal comfort against a minimal energy use. A comparison between best-practice conventional control and MPC allows defining a theoretical potential for performance improvement by applying MPC. However, the real MPC performance decreases in the presence of uncertainties: MPC model mismatch, weather and occupation prediction inaccuracy, measurement errors, but also inaccuracy in the formulation of the cost function and system constraints.

Typically, feedback is introduced into the MPC formulation, using a receding horizon approach, to reduce the effects of uncertainty (Maciejowski, 2002): unmodelled building or installation dynamics, nonlinearities and wrongly or non-predicted disturbances. Higher MPC performance can also be achieved by reducing these uncertainties or by adapting the MPC-formulation to make it more robust against these uncertainties. Typically, the development of the building model in the controller attracts a large attention. However, other parameters might equally influence MPC performance: the description of the cost function, measurement faults, prediction faults, misjudged constraints, ...

The aim of this paper is twofold. First the potential of MPC against a well tuned rule based controller is assessed without building model error: the building is simulated using the same model as in the MPC-loop. Secondly, the sensitivity of the MPC performance against faults occurring in the MPC-loop is analysed. This allows to draw up a priority list of parameters to focus on when improving the MPC or the MPC design procedure, where the parameters with the largest influence should be tackled first.

METHODOLOGY

A simulation model of a South oriented office building zone with concrete core activation and ventilation (Fig. 1) serves as an emulator to generate the building data and test the performance of the control loops. An MPC has been designed for this building (Sourbron, 2012), for which the performance is compared with a well tuned rule based controller (Sourbron and Helsen, 2013a,b). This rule based controller is called the C^4-controller (Constant Concrete Core Control) because it operates to keep the concrete core at a set point of 1^oC above the minimum thermal comfort limit.

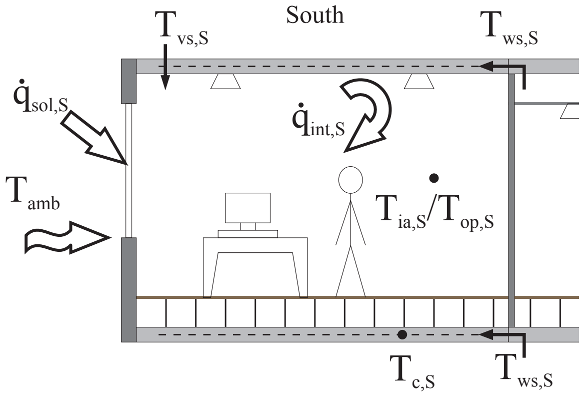

Figure 1: Schematic representation of the South oriented office zone with the disturbances ambient temperature T_{amb}, solar radiation $\dot{q}_{sol}$ and internal gains $\dot{q}_{int}$, the inputs water supply temperature T_{ws} and ventilation temperature T_{vs} and the operative temperature T_{op} and concrete core temperature T_c.

The performance of the control loop is assessed using 6 performance parameters, which are presented in Table 1: primary energy of the CCA-water loop, primary energy of the ventilation air circuit and thermal discomfort in the office zone. Typically for CCA-systems, the CCA-loop is connected to a ground coupled heat pump installation (Franziska Bockelmann, 2013), while the air is conditioned using a standard condensing gas boiler and an air-cooled chiller (details are described by Sourbron (2012)).

A summer day, with only cooling of supply water and supply air, and a winter day, where supply water and supply air are only heated, are investigated. Using this approach, a clear heating-only and cooling-only situation is analysed.

Table 1: Performance parameters for control analysis

Performance parameter	Units	Description
Primary energy for supply water to the CCA, including circulation pump consumption		
E_{wh}	(Wh/m^2)	Heating with heat pump
E_{wc}	(Wh/m^2)	Cooling with direct ground cooling
Primary energy for supply air to the building zone, including fan consumption		
E_{vh}	(Wh/m^2)	Heating with condensing gas boiler
E_{vc}	(Wh/m^2)	Cooling with air-cooled chiller
Thermal discomfort in the office zone		
DC_{un}	(Kh)	Undercooling ($T_z < T_{comfort,min}$)
DC_{ov}	(Kh)	Overheating ($T_z > T_{comfort,max}$)

Three distinct controller situations are analysed and compared: the C^4-controller, the fault-free MPC and the MPC with faults. In the different simulation cases, the plant model (the 'building') and the controller model used in the MPC are equal (Fig. 2 and Eqs. 1-4). It is a reduced building model with one state for the zone temperature T_z and one for the concrete core temperature T_c. Inputs are the water supply temperature T_{ws} and the ventilation supply temperature T_{vs}. Disturbances are the ambient temperature T_{amb}, solar radiation $\dot{q}_{sol}$ and internal gains $\dot{q}_{int}$. The model parameters have been identified by Sourbron et al. (2012) using an identification procedure with data from a detailed emulator model. In each simulation case, the building has low level controllers for the CCA water supply temperature and the ventilation supply temperature.

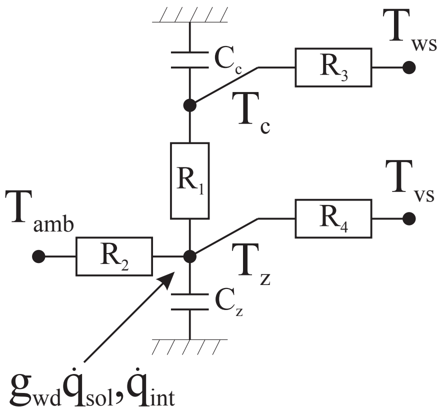

Figure 2: Simplified building representation by means of a 2nd order building model

The system equations and matrices are:

$$\dot{X} = AX + BU \quad (1)$$

$$Y = CX + DU \quad (2)$$

with:

$$X = [T_c; T_z] \quad (3)$$

$$U = [T_{ws}; T_{vs}; T_{amb}; \dot{q}_{int}; \dot{q}_{sol}] \quad (4)$$

To distinguish between the real operative temperature T_{op} of the controlled building, and the estimate of this temperature by the controller building model (Fig. 2), the symbol T_z is used for the latter in this paper. It can be seen as an approximation of the operative temperature T_{op} (Kummert, 2001).

This approach creates for the MPC a completely fault-free reference case: when no measurement, constraint, prediction or cost function faults occur, the T_z-profile predicted by the MPC will be exactly equal to the T_z-profile obtained by simulating the building with the optimised T_{ws}- and T_{vs}-profile as inputs.

In a first step, in order to quantify the potential of the MPC, the MPC-reference case is compared with the tuned rule based controller Sourbron and Helsen (2013a).

In a next step, different 'faults' are introduced in the MPC-loop. A fault is defined as a set point correction, a misjudged control parameter or a sensor error. The MPC receives faulty input data from the building, with this it calculates an optimal 24h-profile for the water supply temperature and the ventilation supply temperature. These profiles, based on the faulty input data, are used as input to the low level controllers of the building, which is simulated without faults. By doing so, the MPC performance can compared with the MPC performance of the reference case.

The different faults introduced in the MPC formulation are listed in Table 2. Faults 1-3 are badly tuned MPC parameters: f1 means that the thermal comfort band ($20-24^oC$ in winter and $23-26^oC$ in summer) is enlarged or decreased with 0.5^oC; f2 and f3 means that the constraint of maximum production power for heating or cooling is misjudged with $\pm10\%$. The faults on measured temperatures (f4-6) can be seen as sensor malfunction and are given a fixed value of $\pm0.5^oC$. Faults f7-8 represent an 10% deviation from the real internal gains and solar gains. Faults f11-16 are misjudged cost function values, for respectively the cost for heating CCA (E_{wh}), for cooling CCA (E_{wc}), for heating ventilation air (E_{vh}), for cooling ventilation air (E_{vc}), for overheating the zone (DC_{ov}) and for undercooling the zone (DC_{un}). The formulation of the cost functions is described in detail by Sourbron (2012).

Table 2: Description of the faults introduced in the MPC formulation

Name	Parameter	Induced fault
f1	$T_{comfortrange}$	$\pm1^oC$
f2	$\dot{q}_{wh,max}$	$\pm10\%$
f3	$\dot{q}_{wc,max}$	$\pm10\%$
f4	meas. T_c	$\pm0.5^oC$
f5	meas. T_z	$\pm0.5^oC$
f6	meas. T_{amb}	$\pm0.5^oC$
f7	$\dot{q}_{int}$	$\pm10\%$
f8	$\dot{q}_{sol}$	$\pm10\%$
f11	cost E_{wh}	$\pm10\%$
f12	cost E_{wc}	$\pm10\%$
f13	cost E_{vh}	$\pm10\%$
f14	cost E_{vc}	$\pm10\%$
f15	cost DC_{ov}	$\pm10\%$
f16	cost DC_{un}	$\pm10\%$

DISCUSSION AND RESULTS ANALYSIS

At first, the fault-free MPC performance is compared with the C^4-controller. The results are shown in Table 3 for respectively the winter and the summer situation. For the winter day, the trade-off between energy and thermal comfort is clearly made by the MPC. While the C^4-controller operates without thermal discomfort, the MPC chooses to allow a small undercooling (which occurs during the first office hour) in order to decrease the CCA heating energy to $52Wh/m^2$. Figs. 3 and 4 show that the MPC chooses for a smaller operation time of the CCA, compared to the C^4-controller: T_{ws} is longer 'on' in the C^4-case. The ventilation supply temperature is equal for both controllers, but the heating energy for ventilation E_{vh} is higher in the MPC case. This is caused by the slightly lower zone air temperature with the MPC (Fig. 3), which reduces the heat recovery rate and forces the heating coil to work harder.

Table 3: Comparison of C^4 control and MPC

		Winter		Summer	
Cost	Units	C^4	MPC	C^4	MPC
E_{wh}	Wh/m^2	80	52	0	0
E_{wc}	Wh/m^2	0	0	127	125
E_{vh}	Wh/m^2	111	126	1	0
E_{vc}	Wh/m^2	0	0	30	3
DC_{ov}	Kh	0.00	0.00	1.14	0.18
DC_{un}	Kh	0.00	0.85	0.00	0.00

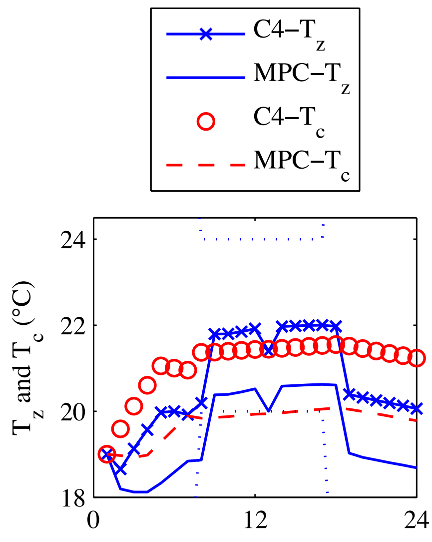

Figure 3: T_z and T_c for C^4-control and MPC, winter situation (dotted line: thermal comfort band)

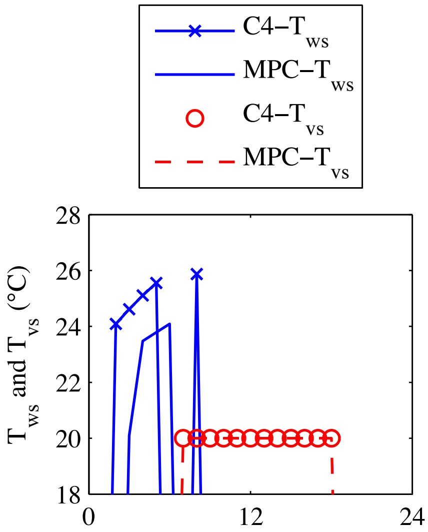

Figure 4: T_{ws} and T_{vs} for C^4-control and MPC, winter situation

For the summer day, Table 3 shows the comparison between the C^4-controller and the MPC. The MPC achieves to reduce the required energy for ventilation air cooling, while CCA cooling remains almost equal, and thermal discomfort is decreased considerably. Fig. 6 shows that the MPC chooses to apply higher ventilation supply temperatures, while it compensates this effect by operating the CCA during a longer period, but with a slightly higher water supply temperature. Using the MPC, the ventilation air is only cooled at hour 15 of the day (Fig. 6). At this hour of the day, the MPC chooses not to use the CCA to cover the heat load peak, but applies the ventilation air instead.

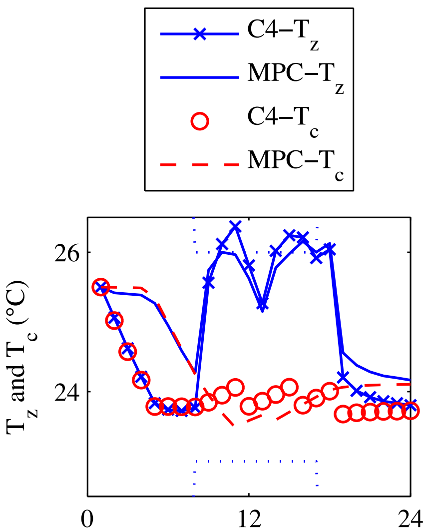

Figure 5: T_z and T_c for C^4-control and MPC, summer situation (dotted line: thermal comfort band)

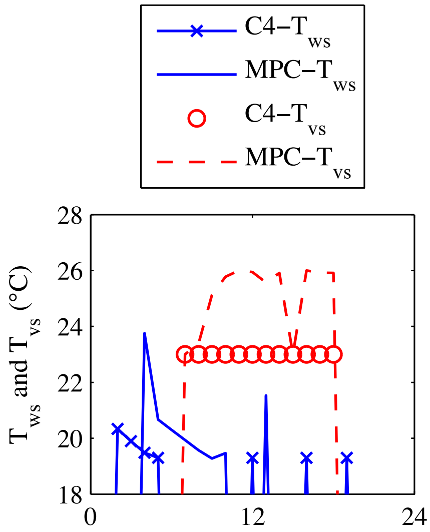

Figure 6: T_{ws} and T_{vs} for C^4-control and MPC, summer situation

In the next step the performance change of the MPC with faults is compared to the reference MPC without faults. Table 4 shows the results for the winter situation, showing the reference case results ('Ref': equal to 1), and the results for each fault in percentage error compared to the 'Ref'-case. The deviation of each of the performance parameters is shown. When the 'Ref'-case has a zero-valued performance parameter, while in the 'fault'-case this parameter is larger than zero, the absolute value is shown between brackets.

Faults f1, f2, f4 and f7 appear to impact considerably the MPC performance. Changing the thermal comfort limits in the MPC (f1) obviously has a large impact, because it forces the MPC to operate in a different temperature range. Enlarging the comfort range (f1-) decreases E_{wh} considerably, but against an important increase of the undercooling hours (located during the first office hours), which are still assessed using the 'normal' comfort range. Decreasing the comfort range has the opposite effect.

Overestimating the available CCA-heating power (f2-) has a limited effect, but increases the thermal discomfort by over 10% (DC_{un}). A fault in measuring the concrete core temperature (f4) has a considerable impact, while a fault on the zone temperature measurement (f5) has no effect on the MPC performance. This is due to the effect that this f5-fault has died out by the beginning of the office hours, which is not the case with the f4-fault. If the MPC would be operating with receding horizon, this would increase the impact of these f4- and f5-fault. Moreover, in the (f4+)-case, where T_c is measured with an error of -0.5^oC, E_{wh} increases and a cooling load E_{wc} is required. Fig. 7 shows how this occurs: a T_{ws}-profile is generated assuming a too low concrete core temperature. This profile is applied to the building and at hour 6, when heating should switch off, the required T_{ws} will be lower than T_c at that moment. Since the CCA supply water energy E_w is proportional to $T_{ws} - T_c$, this means that the CCA water flow is cooling down the concrete, resulting in $E_{wc} = 13.5 Wh/m^2$. On the other hand, E_{wh} increases, because the MPC assumes the CCA is colder than in reality. Compared to T_{ws} in the 'Ref'-case (Fig. 4), the water supply temperature is higher in this case. An option to deal with this fault, is to define correct rules for the low level building controllers, which enforce the input profiles to the building system, so they can compensate for this MPC malfunction.

A fault on the ambient temperature (f6) has a limited effect, while the impact of misjudging the internal gains is large (f7). A fault on the solar gains (f8) has a limited influence, but this is due to the winter situation, with low solar radiation. The faults in cost function values has no effect on the MPC operation. For these cost function values to have a considerable effect, they would need to change with a factor of 50%, but this trade-off between energy and thermal discomfort is more a matter of tuning the MPC than a faulty operation.

Table 4: Sensitivity of MPC performance (energy and discomfort) to faulty parameters

Winter						
	E_{wh} (Wh/m^2)	E_{wc} (Wh/m^2)	E_{vh} (Wh/m^2)	E_{vc} (Wh/m^2)	DC_{un} (Kh)	DC_{ov} (Kh)
Ref	52	0	126	0	0.85	0.00
Fault-versus-Ref Percentage error A value in brackets means the absolute value of that performance parameter is shown when the corresponding 'Ref'-value is zero						
Fault	(%)	(%)	(%)	(%)	(%)	(%)
f1-	-49	0	+4	0	+115	0
f1+	+49	0	-4	0	-45	0
f2-	-2	0	+0	0	+11	0
f2+	+0	0	-0	0	-0	0
f4-	-7	0	+2	0	+41	0
f4+	+30	(13.5)	-2	0	-23	0
f5-	-0	0	+0	0	+1	0
f5+	+0	(0.2)	-0	0	-0	0
f6-	-2	0	+0	0	+6	0
f6+	+4	(0.7)	-0	0	-3	0
f7-	-11	0	+1	0	+27	0
f7+	+15	(2.6)	-1	0	-14	0
f8-	-0	0	+0	0	+1	0
f8+	+1	(0.0)	-0	0	-0	0
f11-	-0	0	-0	0	-0	0
f11+	-0	0	-0	0	-0	0
f13-	-0	0	-0	0	-0	0
f13+	-0	0	-0	0	-0	0
f16-	-0	0	-0	0	-0	0
f16+	-0	0	-0	0	-0	0

For the summer operation, Table 4 shows that the impact of the faults is much larger, certainly on the change in thermal discomfort. Changing the thermal comfort band (f1) has an even larger influence on the MPC performance, compared to the winter situation. This is due to the fact the the MPC operates during the whole period of office hours against the upper thermal comfort limit. A fault in this limit obviously means that the building will be operating outside the limit during almost the whole office hours period.

Table 5: Sensitivity of MPC performance (energy and discomfort) to faulty parameters

Summer						
	E_{wh} (Wh/m^2)	E_{wc} (Wh/m^2)	E_{vh} (Wh/m^2)	E_{vc} (Wh/m^2)	DC_{un} (Kh)	DC_{ov} (Kh)
Ref	0	125	0.1	3	0.00	0.18
Fault-versus-Ref Percentage error A value in brackets means the absolute value of that performance parameter is shown when the corresponding 'Ref'-value is zero						
Fault	(%)	(%)	(%)	(%)	(%)	(%)
f1-	+0	-16	-99	+36	+0	+1186
f1+	+0	+23	+507	-16	+0	-100
f3-	+0	-2	-99	+21	+0	+285
f3+	+0	+0	+99	+0	+0	+0
f4-	(9.3)	+12	+1962	-6	+0	-87
f4+	+0	-4	-99	+57	+0	+726
f5-	(0.1)	+0	+22	-0	+0	-1
f5+	+0	-0	-0	+1	+0	+5
f6-	(0.5)	+8	+2513	-7	+0	-100
f6+	+0	-1	-44	+54	+0	+100
f7-	(2.1)	+11	+1764	-9	+0	-100
f7+	+0	-9	-99	+42	+0	+652
f8-	(0.4)	+2	+331	-1	+0	-21
f8+	+0	-1	-55	+7	+0	+98
f12-	+0	-0	-0	+1	+0	+0
f12+	+0	+7	-0	-6	+0	-100
f14-	+0	-0	-0	-0	+0	-0
f14+	+0	-0	-0	+1	+0	+0
f15-	+0	+7	-0	-6	+0	-100
f15+	+0	-0	-0	-0	+0	-0

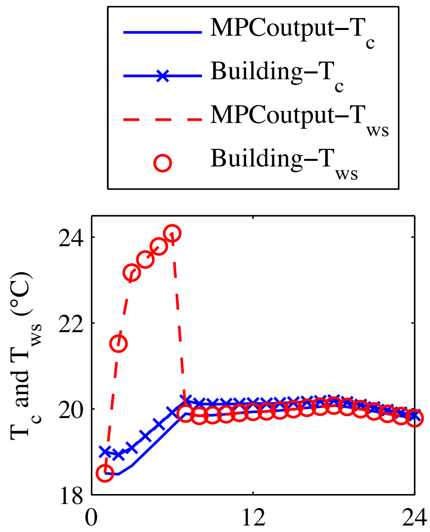

Figure 7: Impact of a $(T_c - 0.5^oC)$ measurement error on the temperatures T_c and T_{ws}, winter situation

The other faults have comparable influence as in the winter situation, but thermal discomfort change is larger due to the effect of working against the comfort limit. Overestimating the available cooling power (f3-) causes a considerable discomfort increase of 285%. A measurement error on T_c (f4-) generates a heating load for the CCA water supply. A prediction error on T_{amb} now has a large impact on the small amount of ventilation heating energy E_{vh}. Prediction errors on $\dot{q}_{int}$ and $\dot{q}_{sol}$ have a comparable impact. Fig. 8 shows that overestimating $\dot{q}_{int}$ causes T_{ws} to be lower than required. Therefore, T_z will be lower than the MPC expects it to be. This impacts both E_{wh} and E_{vh} (Table 4 and Fig. 9), although they are small in absolute values.

In the summer situation, a fault in the cost function does have a impact on the MPC performance. Underestimating the cost of CCA cooling (f12+) causes a shift from cooling with the air to cooling with the CCA and puts the MPC in a save mode, reducing thermal discomfort completely. The same applies for overestimating the cost of overheating (f15-). However, these cost function faults never decrease the MPC performance.

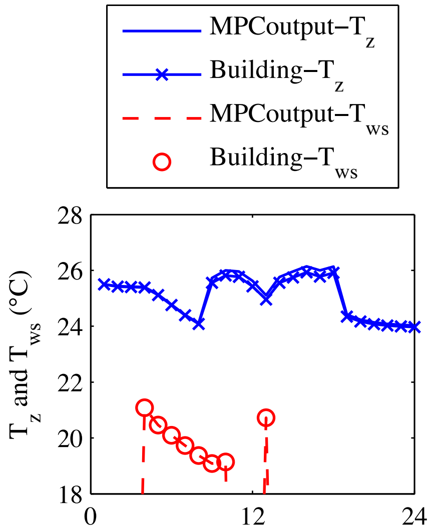

Figure 8: Impact of a $(\dot{q}_{int} + 10\%)$ prediction error on the temperatures T_z and T_{ws}, summer situation

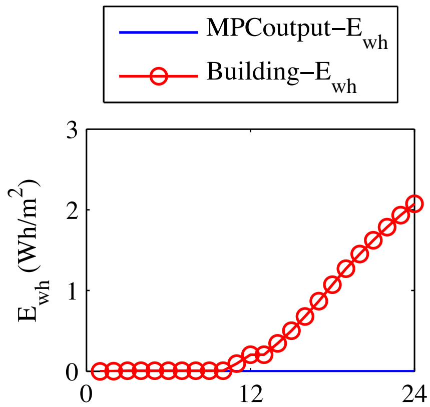

Figure 9: Impact of a $(\dot{q}_{int} + 10\%)$ prediction error on the CCA heating energy use E_{wh}

CONCLUSION

This paper shows that the MPC has a considerable potential in controlling both the slow reacting CCA and the fast reacting ventilation system. However, care should be taken when faults are introduced into the MPC formulation. The thermal comfort limits should comply with the real limits for which the occupants feel comfortable.

An incorrect estimate of the available CCA cooling or heating power, can have a large impact on the thermal discomfort.

Since the concrete core temperature is an important initial condition of the MPC model, a measurement error on this sensor has a large impact on the MPC performance. It can even induce a heating load, where this was absent in the error-free reference case. Measuring the zone temperature is less crucial, because an initial error will fade out more quickly.

Prediction errors of the ambient air temperature, solar and internal heat gains, have a large impact in the MPC summer operation. After all, the MPC is working as close as possible to the upper comfort limit to save on energy, but a small error causes a large trespass of this upper comfort limit. However, in a real time application, these parameters are difficult to predict. Therefore, making the MPC more robust against these faults, seems to be an important task.

Faults in the cost function description do not have an important effect, as long as these faults remain reasonably small.

This analysis shows that it is important to make the MPC-loop robust against occurring faults. This can be achieved by increasing the quality of MPC formulation, or to define correct rules for low level controllers which enforce the calculated input profiles to the building system.

REFERENCES

Franziska Bockelmann, Stefan Plesser, H. S. 2013. *REHVA Guidebook No 20, Advanced system design and operation of GEOTABS buildings*. Federation of European Heating, Ventilation and Air-conditioning Associations.

Kummert, M. 2001. *Contribution to the application of modern control techniques to solar buildings. Simulation-based approach and experimental validation*. PhD thesis, Fondation Universitaire Luxembougoise.

Maciejowski, J. M. 2002. *Predictive Control with Constraints*. Pearson Education Limitedl, Harlow, Essex.

Olesen, B. W. 2000. Cooling and heating of buildings by activating their thermal mass with embedded hydronic pipe system. In *Proceedings of CIBSE/ASHRAE joint conference ??20/20 Vision??*, Dublin.

Parys, W. 2012. *Cost optimization of cellular office buildings based on building energy simulation*. PhD thesis, KU Leuven.

Sourbron, M. 2012. *Dynamic thermal behaviour of buildings with Concrete Core Activation*. PhD thesis, KU Leuven, Leuven.

Sourbron, M. and Helsen, L. 2013a. Sensitivity analysis of feedback control for concrete core activation and impact on installed thermal production power. *Journal of BuildingPerformance Simulation*, submitted.

Sourbron, M. and Helsen, L. 2013b. Slow thermally activated building system and fast air handling unit join forces through the use of model based predictive control. In *CLIMA 2013, 11th REHVA world congress & 8th international conference on IAQVEC*. REHVA.

Sourbron, M., Verhelst, C., and Helsen, L. 2012. Building models for Model Predictive Control of office buildings with Concrete Core Activation. *Journal of Building Performance Simulation*.