Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 122 (2017) 979–984

Energy Procedia

www.elsevier.com/locate/procedia

CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, CISBAT 2017 6-8 September 2017, Lausanne, Switzerland

Smart Buildings (Predictive & Neuro-Fuzzy Control)

Comparison of centralized and decentralized model predictive control in a building retrofit scenario

Theis Heidmann Pedersen[a,]*, Rasmus Elbæk Hedegaard[a], Michael Dahl Knudsen[a], Steffen Petersen[a]

[a]*Department of Engineering, Aarhus University, Inge Lehmanns Gade 10, 8000 Aarhus C, Denmark*

Abstract

Heat transfer between apartments can challenge the positive effects of applying model predictive control (MPC) in multi-apartment buildings. This paper reports on an investigation of how the performance of two different MPC approaches – centralized and decentralized – may be affected by non-insulated and insulated partition walls between apartments. The results suggest that ignoring inter-zonal thermal effects using the less complicated decentralized approach leads to insignificant performance reductions compared to the more complicated centralized approach – especially if partition walls are insulated.

Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale

Keywords: Model predictive control; Building retrofit; Energy flexibility; Residential space heating; Demand response

1. Introduction

Current studies have demonstrated that model predictive control (MPC) of building systems may increase energy efficiency and ensure thermal comfort. MPC schemes rely on a model of the building dynamics, measurements of the state of the building and forecasts of disturbances (e.g. weather and occupancy) to determine a sequence of optimal

* Corresponding author.
E-mail address: thp@eng.au.dk

1876-6102
Peer-review under responsibility of the scientific committee of the CISBAT 2017 International Conference – Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale
10.1016/j.egypro.2017.07.456

control actions [1-3]. Several studies have applied MPC to optimize the operation of heating, ventilation and air conditioning (HVAC) systems and have achieved significant energy savings. Sourbron et al. [2] applied MPC to operate a heat pump in an office building equipped with thermo active building systems, which reduced the electricity consumption by 15% while ensuring thermal comfort. Goyal et al. [3] used MPC to operate an air-handling unit and achieved energy savings of 55-60% compared to a dual-maximum baseline control. In a simulation study, Oldewurtel et al. [1] compared MPC to conventional rule-based control for various building typologies and locations, and found that MPC, in most cases, reduced energy consumption while improving thermal comfort.

Several studies have also considered time-varying energy prices together with MPC to minimize the operational cost, i.e. economic model predictive control (E-MPC), to provide flexibility to the energy grid through demand response [4-7]. A simulation study by Avci et al. [4] used real time prices together with an E-MPC scheme to operate an AC unit in a single residence and reduced the energy consumption in peak-hours by 23.6% and operational cost with 13% compared to a baseline controller. Pedersen et al. [5] used an E-MPC scheme and day-ahead power market prices to investigate the demand response potential in an existing residential multi-apartment building before and after retrofitting the building envelope. Compared to a baseline PI controller, the simulation results suggested that the E-MPC scheme reduced the energy consumption in peak-hours in the existing and retrofitted building by approx. 7% and up to 47%, respectively, while ensuring thermal comfort.

For multi-zone buildings, centralized and decentralized thermal control schemes exist [5, 8, 9]. Centralized MPC schemes require a detailed building model that accounts for heat transfer between adjacent zones to determine the operation in all zones simultaneously. Decentralized MPC relies on a set of single-zone models that neglect inter-zonal heat transfer, leading to multiple detached optimization problems. In theory, decentralized control schemes return a sub-optimal solution compared to centralized MPC. To show this, Moroşan et al. [8] compared a conventional baseline controller with a decentralized and centralized MPC scheme, which achieved energy savings of 5.5% and 13.4%, respectively. However, the authors noted that the performance difference depends on the coupling degree between zones. Pedersen et al. [5] likewise found a minor performance difference between centralized and decentralized control structures when applying E-MPC.

In existing apartment buildings, the interior partition walls often consist of heavy materials with high conductivity, such as concrete. However, in a retrofit situation, where the energy efficiency of the building is increased, insulation is often added to the partition walls to reduce inter-zonal noise. Consequently, the conductivity of the wall is reduced, which may diminish any advantage of including inter-zonal thermal effects. The decentralized control approach may therefore be more practical since it does not require mapping of zone-adjacency during model establishment or exchange information between controlled zones during operation. This paper therefore investigates the performance difference between centralized and decentralized MPC in an apartment building without and with insulated partition walls.

2. Method

The third floor of an existing residential building located in Aarhus, Denmark, consisting of ten apartments and five stairwells was modelled in EnergyPlus (EP) and used to represent the actual building to be controlled. In addition to the existing building, a case with a retrofitted building envelope was considered. Information on geometry and thermal characteristics of the existing and retrofitted buildings are provided in ref. [5] (the retrofitted building is denoted retrofit8 in the reference). The existing partition walls between apartments were assumed to consist of 120 mm concrete while additional 100mm mineral wool and 13mm gypsum was added when insulating the walls.

The MPC scheme was implemented in MATLAB and used to operate the space heating (electrical baseload) of the EP model through co-simulation facilitated by the Building Controls Virtual Test Bed (BCVTB) [10]. The simulations were carried out for the period December 1, 2016 to February 28, 2017, which constitutes the coldest period of the heating season in Denmark, using an EP weather data file based on on-site weather measurements. To ease the interpretation of the results, internal gains originating from occupants and equipment were omitted and perfect weather forecasts were assumed.

2.1. Centralized and decentralized model predictive control

MPC is an optimization-based control scheme, which at each time step determines a sequence of optimal space heating control actions by minimization of a cost function based on an input weight vector c associated with the control actions. The problem (eq. 1a-1g) is solved for a finite prediction horizon N which, in this study, was set to 72 hours. The control actions are restricted by the maximum design power $P_{\max}$ of the heating system (eq. 1d), and eq. 1e and eq. 1f constrain the apartment air temperatures and the temperature rate of change, respectively. Specifications for input and state constraints are listed in Table 1. The control actions are communicated to the space heating system in a receding horizon approach, i.e. only the first control action is implemented and the procedure is then repeated at the next time step based on recent apartment air temperature measurements and updated disturbance forecasts [1].

$$\underset{u_{0|t},\ldots,u_{N|t}}{\text{minimize}} \quad \mathrm{J} = \sum_{n=0}^{N\text{-}1} c_{n|t}^{T} \cdot u_{n|t} \tag{1a}$$

$$\text{subject to} \quad x_{n+1|t} = \mathbf{A}x_{n|t} + \mathbf{B}u_{n|t} + \mathbf{E}d_{n|t} \qquad \forall n = 0,\ldots,N\text{-}1 \tag{1b}$$

$$y_{n+1|t} = \mathbf{C}x_{n+1|t} \qquad \forall n = 0,\ldots,N\text{-}1 \tag{1c}$$

$$0 \leq u_{n|t} \leq P_{\max} \qquad \forall n = 0,\ldots,N\text{-}1 \tag{1d}$$

$$T_{\text{min,n}|t} \leq y_{n+1|t} \leq T_{\text{max,n}|t} \qquad \forall n = 0,\ldots,N\text{-}1 \tag{1e}$$

$$\Delta T_{\text{min,n}|t} \leq \frac{y_{n+1|t}}{\Delta\tau} \leq \Delta T_{\text{max,n}|t} \qquad \forall n = 0,\ldots,N\text{-}1 \tag{1f}$$

$$x_{0|t} = x_t \tag{1g}$$

The MPC scheme requires a reduced-order model that adequately describes the thermodynamics of the building, e.g. grey-box models. Grey-box models are characterized by having a pre-specified model structure consisting of physically meaningful parameters that are estimated from measurement data through methods from the field of system identification [11]. In a multi-apartment building, the model represents an interconnected system of subsystems (corresponding to apartments), where the interactions occur due to conduction between apartments [12]. Identifying suitable multi-zone models for centralized control schemes, thus considering the thermal interactions, can be difficult and requires time-consuming experiments, planning and modeling [12, 13]. Decentralized control schemes neglect the interactions and treat the thermal influences between subsystems as external unknown disturbances, thus adequate models are easier to identify. In this study, a two-state grey-box apartment model was used, where the two states represent the lumped thermal capacity of the zone air and the constructions. The applied state space representation is given in (1b-1c) with state matrix **A**, system states x for time step $t+n$ forecasted at time t, input matrix **B**, control actions u, disturbance matrix **E**, disturbances d, output matrix **C** and output y (i.e. apartment air temperatures).

Table 1. Specification of input and state constraints

		Apt. 1	Apt. 2	Apt. 3	Apt. 4	Apt. 5	Apt. 6	Apt. 7	Apt. 8	Apt. 9	Apt. 10
Area	[m^2]	81	94	81	94	81	94	81	94	50	94
$P_{\max}$	[W/m^2]	50	50	50	50	50	50	50	50	50	50
$T_{\min}$	[°C]	20	22	20	22	20	22	20	22	20	22
$T_{\max}$	[°C]	24	26	24	26	24	26	24	26	24	26
$\Delta T_{\min}$	[°C/h]	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1	-2.1
$\Delta T_{\max}$	[°C/h]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1

The centralized and decentralized MPC schemes were first evaluated in terms of their ability to track the lower comfort bounds, which constitutes the most energy efficient control approach. Secondly, the MPC schemes' ability to achieve end-user cost savings was assessed by considering time varying energy prices as input weights. Historical day-ahead power market prices for the simulation period were used, cleared for the bidding area western Denmark (DK1). For the sake of simplicity, taxation of electricity was omitted, thus results presented in absolute values are not directly comparable to actual costs paid by building owners.

3. Results and discussion

The ability of the centralized and decentralized MPC schemes to track the lower comfort bound for one week in apartment 9 in the retrofitted building, with and without insulated partition wall is displayed in Figure 1. For the building with existing partition walls, the centralized MPC scheme kept the air temperature close to the temperature set-point, whereas the decentralized MPC scheme overestimated the heating demand, leading to a positive temperature offset compared to the temperature set-point. The positive offset was caused by heat gains from adjacent apartments with higher temperature set-points (see Table 1). When insulating the partition walls, the heat exchange between adjacent apartments was reduced, resulting in a similar performance of the centralized and decentralized MPC schemes.

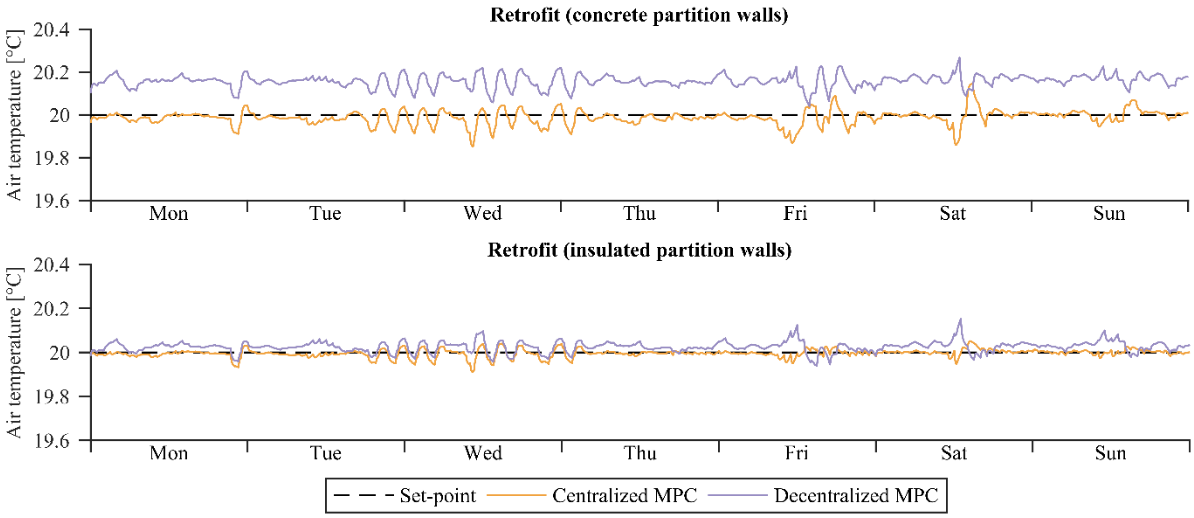

Figure 1. Simulation results of the room temperature in apt. 9 during one week.

The mean biased error (MBE) between the temperature set-points and the resulting air temperatures during the entire simulation period is specified in Table 2 (+ indicates insulated partition walls). The MBE supports the observations in Figure 1, where the decentralized MPC scheme in buildings with existing concrete partition walls led to positive and negative offsets for the apartments with a set-point of 20°C and 22°C, respectively. In the case with the insulated partition walls, the MBE for the two control schemes were very similar. In some apartments, the decentralized MPC scheme even achieved better results than centralized MPC, presumably because the required multi-apartment model was more difficult to identify than the single-apartment models, which led to a significant increase in the uncertainty of the parameter estimates [5].

Table 2. Mean biased error

Building	Control	Apt. 1	Apt. 2	Apt. 3	Apt. 4	Apt. 5	Apt. 6	Apt. 7	Apt. 8	Apt. 9	Apt. 10
Existing	Centralized	0.00	0.01	0.00	0.02	0.00	0.01	0.02	0.02	0.00	0.01
	Decentralized	0.06	-0.09	0.10	-0.07	0.12	-0.04	0.07	-0.07	0.12	-0.03
Existing+	Centralized	-0.01	0.03	-0.02	0.03	-0.01	0.01	-0.01	0.02	0.01	0.00
	Decentralized	0.01	-0.01	0.03	-0.01	0.03	-0.01	0.02	-0.01	0.03	0.00
Retrofit	Centralized	-0.01	0.03	-0.01	0.02	-0.02	0.02	-0.01	0.04	-0.02	0.00
	Decentralized	0.06	-0.09	0.10	-0.09	0.11	-0.05	0.06	-0.08	0.17	-0.05
Retrofit+	Centralized	-0.03	0.03	-0.02	0.02	-0.02	0.02	-0.04	0.03	0.00	-0.01
	Decentralized	0.00	-0.02	0.02	-0.02	0.02	-0.01	0.01	-0.02	0.03	-0.01

The mechanism of a conventional PI-controller and the E-MPC schemes using historical day-ahead prices during one week are displayed in Figure 2 for the retrofitted building with the existing partition walls and with insulated partition walls. In both cases, the conventional PI-controller maintained the air temperature close to the specified lower comfort set-point of 20°C at all times. The E-MPC schemes, however, exploited the structural thermal mass to reduce the space heating consumption in high price periods by increasing the air temperature within the comfort bounds at times with low prices. Since the optimal control actions depend on the state of the building at any given time, direct comparison between the two control schemes at each time instance should be done carefully. However, in the case with the existing concrete partition walls, discrepancies between the two E-MPC schemes are clearly distinguishable on Thursday and Friday, where only the centralized E-MPC scheme increased the temperature. Furthermore, the temperature offset of the decentralized control scheme identified previously was also apparent in the case with the concrete partition walls. For the insulated partition walls, the control schemes led to almost identical operations.

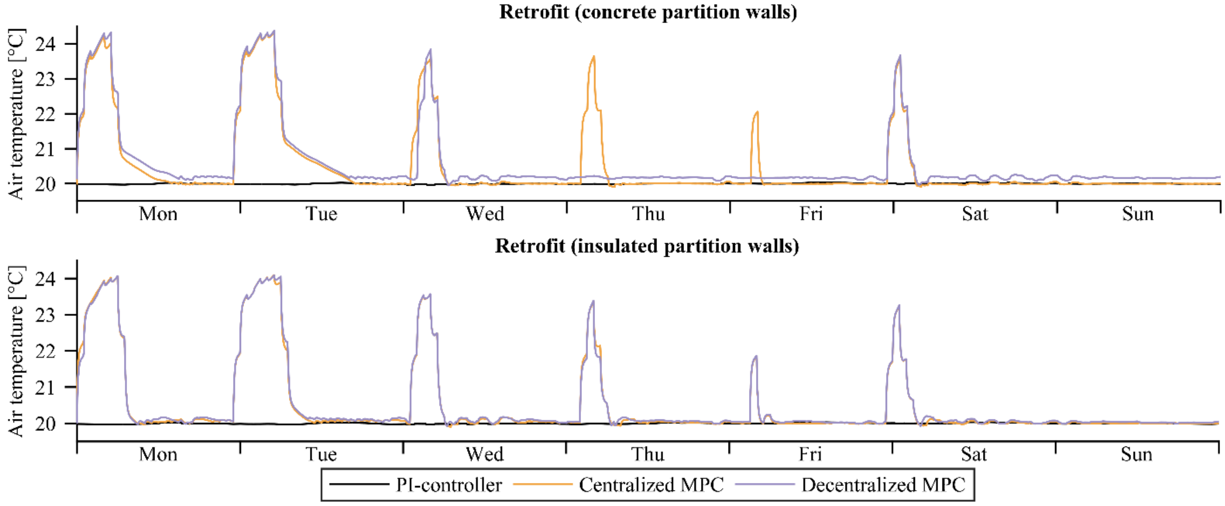

Figure 2. Simulation results of the room temperature in apt. 9 during one week using E-MPC.

Table 3 lists the total costs of each of the three control schemes (PI, centralized E-MPC and decentralized E-MPC) for the four building cases: before and after a general retrofit of the building envelope and with and without insulated partition walls. Furthermore, the total achieved cost savings and mean comfort violations compared to the PI-controller are specified. The standard deviations across the apartments are specified in the parentheses. The results suggest that centralized and decentralized E-MPC schemes achieved total cost savings similar to those of the PI controller. The decentralized control scheme, however, tended to distribute cost savings unevenly between the apartments in the scenarios without insulated partition walls. Further inspection of the simulation results indicated that this was due to lower achieved cost savings in the apartments with a lower comfort bound of 20°C; here, the E-MPC scheme planned the heating operation without considering the heat gains from adjacent apartments. This effect was significantly reduced in the scenarios with insulated partition walls. Furthermore, in the case with the insulated partition walls, the decentralized control scheme out-performed the centralized control scheme in terms of maintaining comfort, presumably because the multi-zone models are more challenging to identify.

Table 3. Summarized simulations results for all ten apartments

Building	Control	Total cost	Cost savings	Relative cost saving	Mean comfort violations
Existing	PI	€ 1040			89.7 (4.3) °Ch
	Centralized	€ 1010	€ 30 (0.66)	2.9%	18.1 (9.8) °Ch
	Decentralized	€ 1011	€ 29 (1.37)	2.8%	22.7 (9.4) °Ch
Existing+	PI	€ 1001			84.4 (2.9) °Ch
	Centralized	€ 977	€ 24 (0.42)	2.4%	15.9 (2.6) °Ch
	Decentralized	€ 979	€ 22 (0.50)	2.2%	11.2 (1.5) °Ch
Retrofit	PI	€ 327			43.9 (3.0) °Ch
	Centralized	€ 293	€ 34 (0.86)	10.4%	9.3 (8.7) °Ch
	Decentralized	€ 293	€ 34 (1.59)	10.4%	18.0 (8.7) °Ch
Retrofit+	PI	€ 323			38.5 (1.7) °Ch
	Centralized	€ 287	€ 36 (0.55)	11.1%	7.5 (3.0) °Ch
	Decentralized	€ 287	€ 36 (0.63)	11.1%	6.9 (2.2) °Ch

4. Conclusion

This paper reports on a simulation-based study of the performance differences between centralized and decentralized MPC schemes for optimal space heating operation in an existing and retrofitted multi-apartment building. The results of a 90-day simulation period showed that the decentralized MPC in buildings without insulated partition walls tended to result in a constant offset from the specified temperature set-point. Consequently, the achieved total cost savings for both schemes were found to be similar, but the decentralized control scheme failed to distribute the savings evenly across all apartments. Insulating the partition walls reduced the constant temperature offsets when applying the decentralized control scheme, which was reflected in the results. The decentralized control scheme was not only able to distribute cost savings evenly, but it also out-performed centralized control in terms of maintaining temperatures within the comfort bounds. This reversal in the optimal approach is likely caused by the fact that the advantages of centralized control diminish as insulation is added between zones, combined with the fact that the more complicated setup of the centralized control was more prone to uncertainty issues when identifying a building model for MPC.

Overall, the results suggest that decentralized control schemes can be applied in multi-apartment buildings, especially where partition walls are insulated for noise-reduction purposes. However, it is difficult to specify a general level of insulation, as the performance depends e.g. on the building, the modeling technique and the control purpose. Applying decentralized MPC also simplifies and reduces the time-consuming work involved when implementing MPC schemes. Furthermore, decentralized control schemes allow apartment owners to specify control objectives themselves, just as it allows for individual apartment owners to decide if and when to invest in advanced control.

Acknowledgements

The authors gratefully acknowledge the support of this work from the project “READY.dk” financed by the Danish energy research and development program ForskEl (grant number: 12305) and the project 'Resource Efficient Cities Implementing Advanced Smart City Solutions' (READY) financed by the 7th EU Framework Programme (FP7-Energy project reference: 609127).

References

[1] F. Oldewurtel, A. Parisio, C. N. Jones, D. Gyalistras, M. Gweder, V. Stauch, B. Lehmann and M. Morari. Use of Model Predictive Control and Weather Forecasts for Energy Efficient Building Climate Control. Energy Build. 45 (2012) 15-27.

[2] M. Sourbron, C. Verhelst and L. Helsen. Building models for model predictive control of office buildings with concrete core activation. J. Build. Perform. Simul. 6 (3) (2013) 175-198.

[3] S. Goyal, H. A. Ingley and P. Barooah. Occupancy-based zone-climate control for energy-efficient buildings: Complexity vs. performance. Appl. Energ. 106 (2016) 209-221.

[4] M. Avci, M. Erkoc, A. Rahmani and S. Asfour. Model predictive HVAC load control in buildings using real-time electricity pricing. Energy Build. 60 (2013) 199-209.

[5] T. H. Pedersen, R. E. Hedegaard and S. Petersen. Space heating demand response potential of retrofitted residential apartment blocks. Energy Build. 141 (2017) 158-166.

[6] M. D. Knudsen and S. Petersen. Demand response potential of model predictive control of Space heating based on price and carbon dioxide Intensity signals. Energy Build. 125 (2016) 196-204.

[7] R. Halvgaard, N. K. Poulsen, H. Madsen and J. B. Jørgensen. Economic Model predictive Control for Building Climate Control in a Smart Grid. in IEEE PES Innovative Smart Grid Technologies (ISGT) (2012) 1-6, Washington, D.C., United States.

[8] P.-D. Moroşan, R. Bourdais, D. Dumur and J. Buisson. Building temperature regulation using a distributed model predictive control. Energy Build. 42 (2010) 1445-1452.

[9] V. Chandan and A. G. Alleyne. Decentralized Architectures for Thermal Control of Buildings. in American Control Conference (2012), Montreal, Canada.

[10] M. Wetter. Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed. J. Build. Perform. Simul. 3 (4) (2010) 1-19.

[11] R. E. Hedegaard and S. Petersen. Evaluation of Grey-Box Model Parameter Estimates Intended for Thermal Characterization of Buildings. in 11th Nordic Symposium on Building Physics (2017), Trondheim, Norway.

[12] S. Goyal, C. Liao and P. Barooah. Identification of multi-zone building thermal interaction model from data. in 50th IEEE Conference on Decision and Control (2011), Orlando, FL, USA.

[13] C. Agbi, Z. Song and B. Krogh. Parameter Identifiability for Multi-Zone Building Models. in 51st IEEE conference on Decision and Control (2012), Maui, Hawaii, USA.