

On Predicted Mean Vote Optimization in Building Climate Control

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Abstract—Low energy buildings have been attracting much attention lately. Most of the research is focused on the building construction or alternative energy sources. Recently, there has been an intense research in the area of Model Predictive Control (MPC) for buildings. The main principle of such a controller is a trade-off between energy savings and user welfare making use of predictions of disturbances acting on the system (ambient temperature, solar radiation, occupancy, etc.). Usually, the thermal comfort is represented by a static range for the operative temperature according to the international standards. By contrast, this paper is devoted to the optimization of the Predicted Mean Vote (PMV) index which, opposed to the static temperature range, describes user comfort directly. PMV index, however, is a nonlinear function of various quantities, which makes the problem more difficult to solve. The paper will show the main differences in MPC problem formulation, compare the control performance both to the conventional and predictive control strategies, point out that the proposed optimal control problem formulation shifts the savings potential of classical MPC by additional 11 % and finally, the quality of the fulfillment of the thermal comfort will be addressed.

I. INTRODUCTION

Buildings account for 20–40 % of the total final energy consumption and its amount has been increasing at a rate 0.5–5 % *per annum* in developed countries [1]. Thanks to developments in the field of mechanical and civil engineering, building energy demands can be reduced significantly. Most of the conventional energy reduction solutions, however, require considerable investments for new technologies. By contrast, energy savings with minimal additional cost can be achieved by improvement of building automation system.

Recently, there has been an intensive research in the field of Model Predictive Control (MPC) for buildings. The aim of MPC is to design a control strategy that minimizes the energy consumption (or operational costs) while guaranteeing that comfort requirements are met. A comprehensive and up-to-date overview of the literature related to the predictive control of buildings can be found on the website of the OptiControl project (www.opticontrol.ethz.ch). From the wide variety of results, a few instances can be listed. The controller *i*) takes disturbance predictions (occupancy, weather etc.) into account, thus it adjusts control actions appropriately [2], [3], *ii*) can utilize the thermal mass of a building in a better way compared to the conventional control strategies (e.g. weather compensated or rule based control) [4], [5], *iii*) is able to deal with variable energy price that can be easily included into the formulation of the

optimization problem [6], [7], *iv*) can handle minimization of the energy peaks within certain time frame [8], [9] (beneficial because of both the possibility of tariff selection and lowering operational costs). There have also been some experimental setups of MPC which have proven the energy savings potential [2], [7], [10] (15–30 % compared to conventional control strategies).

As already stated, the focus of MPC is not only on the minimization of costs or consumed energy, but it also aims at the fulfillment of comfort requirements, which have, so far, been defined by operative or air temperature band that is derived from more general thermal comfort indices (according to the international standards [11], [12]). From the analysis of MPC performance, it turns out that the control strategy always tries to track the lower/upper boundary of the reference trajectory, which may, however, deteriorate the comfort quality from a longer perspective or, on the other hand, keep a distance from the boundaries of the thermal comfort index. The key aim posed in this study is to quantify the level of deterioration/reserves, in sense of the thermal comfort index, caused by the tracking of the temperature band boundaries. To do so, the most widely used thermal comfort index Predicted Mean Vote (PMV) is selected.

PMV was developed by Fanger [13], who produced a set of equations which includes parameters that influence thermal comfort. Among others, these are air velocity, relative humidity, metabolic rate, etc. This index will also be explicitly implemented into MPC cost function which, however, results in a nonlinear optimization problem, for which the main differences from the classical MPC problem will be outlined. Performance of the controllers will be studied on a two zone office building which is for this purpose modeled using TRNSYS environment [14].

This study is inspired by a pioneering work in which the authors explicitly included PMV index into optimization problem [15]. To our knowledge, there is no other paper dealing with PMV optimization within MPC framework. The results of the authors are extended by the assessment of the comfort quality for various control strategies as well as by considering more decision variables in the optimization problem, i.e. mean radiative temperature is taken into account as it is one of the main factors affecting the thermal comfort [16].

The paper is further organized as follows. The Section II introduces the thermal comfort measures. Section III describes the building simulator which is further used in the controller performance comparisons. The next Section IV states the control problems. Section V summarizes the results and Section VI concludes the paper and states future work.

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TABLE I
QUANTITIES DEFINING THE THERMAL COMFORT

Symbol	Quantity	Typical values	Units	Values considered further in the study
M	Metabolic rate	46–232	W/m ²	70 W/m ² =1.2 met, i.e. sedentary activity (office, dwelling, school, etc.)
W	Effective mechanical power	≥ 0	W/m ²	0 W/m ²
I_{cl}	Clothing insulation	0–0.31	m ² K/W	0.155 K/W=1 clo, i.e. common indoor clothing for a winter time
f_{cl}	Clothing surface area factor	0–1	-	depends on I_{cl} (see (5))
t_a	Air temperature	10–30	°C	derived decision variable from system inputs
\bar{t}_r	Mean radiant temperature	10–40	°C	derived decision variable from system inputs
v_{ar}	Relative air velocity	0–1	m/s	0.1 m/s, i.e. typical for offices
p_a	Water vapor partial pressure	0–2700	Pa	relative humidity assumed to be fixed at $\phi = 50\%$
h_c	Convective heat transfer coefficient	0–12.1	W/(m ² K)	Depends on the air and cloth temperatures according to (4)
t_{cl}	Clothing surface temperature	10–30	°C	Depends on multiple quantities, see (3)

$$PMV = (0.303 \cdot \exp(-0.036 \cdot M) + 0.028) \cdot L, \quad (1)$$

$$L = (M - W)$$

$$- 3.05 \cdot 10^{-3} \cdot (5733 - 6.99 \cdot (M - W) - p_a) - 0.42 \cdot ((M - W) - 58.15)$$

$$- 1.7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0.0014 \cdot M \cdot (34 - t_a)$$

$$- 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot ((t_{cl} + 273)^4 - (\bar{t}_r + 273)^4) - f_{cl} \cdot h_c \cdot (t_{cl} - t_a), \quad (2)$$

$$t_{cl} = 35.7 - 0.028 \cdot (M - W) - I_{cl} \cdot (3.96 \cdot 10^{-8} \cdot f_{cl} \cdot ((t_{cl} + 273)^4 - (\bar{t}_r + 273)^4) + f_{cl} \cdot h_c \cdot (t_{cl} - t_a)), \quad (3)$$

$$h_c = \begin{cases} 2.38 \cdot |t_{cl} - t_a|^{0.25} & \text{if } 2.38 \cdot |t_{cl} - t_a|^{0.25} \geq 12.1 \cdot \sqrt{v_{ar}} \\ 12.1 \cdot \sqrt{v_{ar}} & \text{if } 2.38 \cdot |t_{cl} - t_a|^{0.25} < 12.1 \cdot \sqrt{v_{ar}} \end{cases}, \quad (4)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \cdot I_{cl} & \text{if } I_{cl} \leq 0.078 \\ 1.05 + 0.645 \cdot I_{cl} & \text{if } I_{cl} > 0.078 \end{cases}. \quad (5)$$

II. THERMAL COMFORT

Thermal comfort in buildings is usually evaluated using the operative temperature [11], which is, in the simplest way, defined as the average of the air temperature and the mean radiant temperature (area weighted mean temperature of the surrounding surfaces [17]). However, the thermal comfort is a more complicated quantity and, in accordance with ISO 7730 [11] and ASHRAE 55 [12] international standards, it can be defined in a more general way, “*The condition of mind which expresses satisfaction with the thermal environment*”, pointing out that it is a cognitive process influenced by various quantities, physical activity, physiological and psychological factors.

There has been a lot of studies on the calculation of the thermal comfort conditions and the most widely used thermal comfort index is the Predicted Mean Vote (PMV) index developed by Fanger in the seventies [13] who introduced a set of equations (1)–(5) which includes parameters that influence thermal comfort of a human being. The PMV index predicts the mean value of the votes of a large group of people based on the heat balance of a human body. The quantities arising in the equations are listed in the Table I. Note that most of the quantities/parameters can be obtained in a rather straightforward way, e.g. air temperature, velocity and humidity as well as surface temperatures can be obtained by direct measurement, while clothing parameters and human activity can be estimated from the prior knowledge about the workload of the occupants.

Thermal balance is achieved when the heat losses to the

TABLE II
DESIGN CRITERIA FOR OFFICE SPACES (HEATING SEASON)

ISO 7730	Operative temperature range	PMV range	PPD [%]
Class A	22 ± 1	0 ± 0.2	< 6
Class B	22 ± 1.5	0 ± 0.5	< 10
Class C	22 ± 2.5	0 ± 0.7	< 15

environment are equal to the heat produced by the human body. Hence, PMV consists of all heat transfers related to the human body. In the equation (1) for PMV index, the symbol L stands for the thermal load of the body (in W/m²) which can be further decomposed (according to the rows in (2)) to *i*) difference between internal and external work, *ii*) heat loss caused by the evaporation from the skin, *iii*) respiration heat losses, *iv*) radiation and convection from the body to the environment.

The PMV index is defined on a 7-level thermal sensation scale: 0 neutral, ±1 slightly warm/cool, ±2 warm/cool, ±3 hot/cold. Then the objective of indoor climate control in the office buildings is to keep PMV index or operative temperature within ranges defined in Table II [11].

Then, based on the PMV index, quantitative measure of the thermal comfort of a group of people is defined by Predicted Percentage Dissatisfied (PPD) index according to (6)

$$PPD = 100 - 95 \exp(-0.0335 \cdot PMV^4 - 0.218 \cdot PMV^2). \quad (6)$$

Note that even if PMV index is zero, there is 5% of dissatisfied occupants.

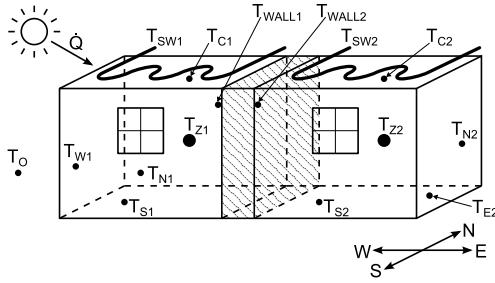


Fig. 1. A scheme of the modeled building

TABLE III
NOTATION OF THE QUANTITIES IN THE SYSTEM

Notation	Description
T_o	Ambient temperature
T_{sw1}	Supply water temperature, zone 1
T_{sw2}	Supply water temperature, zone 2
\dot{Q}	Total solar radiation
T_{c1}	Ceiling core temperature, zone 1
T_{s1}	Core temperature measured on south side, zone 1
T_{w1}	Core temperature measured on west side, zone 1
T_{n1}	Core temperature measured on north side, zone 1
T_{z1}	Zone temperature, zone 1
T_{c2}	Ceiling core temperature, zone 2
T_{s2}	Core temperature measured on south side, zone 2
T_{e2}	Core temperature measured on east side, zone 2
T_{n2}	Core temperature measured on north side, zone 2
T_{z2}	Zone temperature, zone 2
T_{wall1}	Core temperature measured on east side, zone 1
T_{wall2}	Core temperature measured on west side, zone 2

III. BUILDING SIMULATOR

The building, schematically outlined in Fig. 1, was constructed in TRNSYS environment using Type56 [14]. It is a medium weight office building with two zones separated by a concrete wall. Both zones have the same dimensions ($5 \times 5 \times 3$ m) and the south oriented walls of the zones involve a window (3.75 m^2). Such a system structure was chosen because it also involves transitional properties between zones. The Heating Ventilation and Air Conditioning (HVAC) system used in the building is of active layer type. Technically, the HVAC system consists of a set of metal pipes placed in the ceiling distributing supply water which then enables thermal exchange with the concrete core of the modeled building. Both zones are equipped with a separate heating circuit where the mass flow rate of the supply water is held constant and then, the supply water temperature is the only manipulated variable in a particular heating circuit. Outside environmental conditions (involving ambient temperature, outside air relative humidity and solar characteristic) are simulated using TRNSYS Type15 with the year weather profile corresponding to Prague, Czech Republic.

For purposes of model identification and subsequent model predictive control, the link between TRNSYS and Matlab was established based on TRNSYS Type155. Time-step of the simulation was set to $T_s = 0.25$ h. This time-step guarantees proper convergency of TRNSYS internal algorithms.

All temperatures and solar radiation depicted in Fig. 1 are assumed to be perfectly measured as they are passed

through the communication link or precomputed in case of the disturbances. The meaning of the quantities is explained in the Table III.

First of all, the communication link was used to generate identification data in order to identify a simple model for control purposes. Pseudo random binary sequence was used as the excitation input signal. The model of the system was identified using grey box technique¹ adopted from [2, Section 3.1.2]. The resulting model has the structure

$$x(k+1) = Ax(k) + Bu(k) + Ww(k), \quad (7)$$

where k is the discrete time, $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, $w \in \mathbb{R}^v$ and A , B , W are the matrices of appropriate dimensions. The vector of system states is composed as $x = [T_{c1}, T_{wall1}, T_{s1}, T_{w1}, T_{n1}, T_{z1}, T_{c2}, T_{wall2}, T_{s2}, T_{e2}, T_{n2}, T_{z2}]^T$, inputs $u = [T_{sw1}, T_{sw2}]^T$ and disturbances $w = [T_o, \dot{Q}]^T$. The sampling period of the model was the same as the time-step of TRNSYS simulation, i.e. $T_s = 0.25$ h. Note that t_a is equivalent to the zone temperature T_z while \bar{t}_r is the area weighted mean temperature of the walls (the rest of system state).

IV. CONTROL PROBLEM FORMULATIONS

Having a linear time invariant model and building simulator in hand, we can develop control strategies in order to *i)* formulate a control strategy which directly optimizes thermal comfort index violations, *ii)* draw conclusions about the amount of required energy and comfort violations (in terms of PMV index) of conventional, predictive and proposed control strategies. To do so, controllers will be validated for three different office building comfort requirements defined by ISO 7730, i.e. Classes A–C (see Table II). Some of the quantities influencing the thermal comfort will be assumed to be constant, for values see Table I.

A. Conventional control strategy

From the conventional strategies, the weather compensated control has been chosen as a representative, because it is commonly used in the buildings of our interest [2], [18]. It is a feedforward control strategy where the temperature of the supply water T_{sw} is set according to the ambient temperature T_o and desired zone operative temperature $T_{z,desired}$ by means of predetermined heating/cooling curves f_{wc} , that is

$$T_{sw} = f_{wc}(T_o, T_{z,desired}). \quad (8)$$

B. Classical MPC formulation for buildings

On the contrary, commonly used MPC strategy solves the optimization problem (9) in a receding horizon fashion. To isolate the impact of the particular control strategy, perfect knowledge of the disturbances is assumed on the prediction horizon. Moreover, the full system state is measured as it is transferred through the link at each simulation time-step. The prediction horizon is set to six hours, i.e. $N = 6/T_s = 24$ samples.

¹The prior knowledge of the system structure can be included into identification algorithm, which at the end results in a better model for control compared to pure black-box techniques [2].

$$\min_u \sum_{k=0}^{N-1} \sum_{i=1}^2 \underbrace{|(T_{sw,i}(k) - T_{c,i}(k))R|_1^1}_{\text{Energy minimization}} + \underbrace{|(T_{z,i}(k) - z_i(k))Q|_2^2}_{\text{Reference tracking}}$$

s.t.: linear dynamics (7),

$$T_{sw,min} \leq T_{sw,i} \leq T_{sw,max},$$

$$T_{z,min} \leq z_i(k) \leq T_{z,max}.$$

Note that Q and R are weighting matrices of appropriate size for tuning the algorithm while $T_{z,min}$ and $T_{z,max}$ are the limits defined by the particular class of ISO 7730 standard (see Table II). The term z_i refers to the slack variable on the zone temperature and expresses that the cost increases only if there is a violation of the reference band.

Note that one norm for weighting of the consumed energy is used, as the term is proportional to the energy². YALMIP optimization toolbox [19] with SDPT3 solver³ were used to define and solve the optimization problem.

C. PMV index in MPC cost function

The last approach is to include optimization of the thermal comfort index PMV directly into the cost function, i.e. to minimize PMV or to try to keep PMV in a certain range and to penalize only violations, which leads to a formulation with the aid of slack variables p_i in (10).

$$\min_u \sum_{k=0}^{N-1} \sum_{i=1}^2 \underbrace{|(T_{sw,i}(k) - T_{c,i}(k))R|_1^1}_{\text{Energy minimization}} + \underbrace{|(PMV_i(k) - p_i(k))Q|_2^2}_{\text{PMV minimization}}, \quad (10)$$

s.t.: linear dynamics (7),

$$T_{sw,min} \leq T_{sw,i} \leq T_{sw,max},$$

$$PMV_{min} \leq p_i(k) \leq PMV_{max},$$

PMV equations (1)–(5).

PMV_{min} and PMV_{max} are defined by the particular class of ISO 7730 norm (see Table II). The same assumptions as for the classical MPC formulation hold here.

The optimization problem (10) is non-convex in the cost function as well as in the constraints, therefore a general nonlinear solver, e.g. `fmincon` from Optimization Toolbox for Matlab, must be employed. Note that Genetic Algorithms (GA) can be viewed as an alternative framework for obtaining a solution to the problem (10). Benefits of GA are mainly such that the optimization process may not end in some local minima. This is however for the price of higher computational demands. Therefore, `fmincon` is used in this work. Increased problem complexity, however, requires a decrease in a prediction horizon length in order to obtain a computationally tractable problem. In this case, the prediction horizon was set to two hours, i.e. $N = 2/T_s = 8$ samples.

²TRNSYS assumes the constant supply water temperature in the ceiling pipes, therefore the difference between supply water and ceiling temperature is commensurate with the consumed energy.

³<http://www.math.nus.edu.sg/~mattokc/sdpt3.html>

Monthly simulations for all thermal comfort classes and controllers were compared and the summary is shown in Figs. 2–4. In the following discussion, the control strategies will be referred to as *i*) P1: weather compensated control according to (8) *ii*) P2: classical MPC formulation, i.e. problem (9) *iii*) P3: MPC formulation with PMV index explicitly specified in the cost function, i.e. equation (10). The predictive strategies were tuned such that there was high stress on the comfort satisfaction, i.e. Q was selected much higher than R .

Time-series for the particular control strategies and ISO 7730 Class C are depicted in Fig. 2. The simulation length is one month, and the winter conditions are considered. Because of the similarity of the signals for the first and the second zone, the signals for the first zone are depicted only. Supply water temperatures are shown in the upper part of the figure and one can see that in case of P1, the supply water follows the trends of the ambient temperature (there is no change in the desired temperature, i.e. the reference is in the middle of the comfort range) while in cases P2 and P3, the controllers compensate both ambient temperature and solar radiation (the second part of the figure). Higher magnitude of supply water temperature in case P3 is caused by the shorter prediction horizon because in such a situation, the controller cannot react in advance to the abrupt changes of the weather. Nonetheless, the lowest value of the supply water temperature of all strategies occurs for problem P3. In this case, even the temperatures of walls and air are lower, which can be seen in the third part of the figure. Although the temperatures in case P3 are lower than in P2, the thermal conditions fulfill the thermal comfort requirements defined by the standard. This is the place where the formulation of P3 can bring further energy savings as the solution to P2 keeps distance from the PMV boundaries.

The same feature can be observed even from the Fig. 3 (consumed energy vs. PMV comfort range violations). It is clear that when using the same class of ISO norm, the P3 approach consumes 11 % less energy than P2 and at the same time, satisfies thermal comfort at almost all instants.

The last Fig. 4 shows assessment of PPD (for definition, see (6)) where P3 control strategy has mean value always tightly below the boundary for comfort (marked by magenta lines), while P2 keeps substantial distance from the boundary.

Note that for thermal comfort class A, the conclusions cannot be drawn due to the large amount of thermal comfort violations (notice the scale on the Fig. 3). It is caused by the tight comfort range (both in the sense of PMV and temperature range) and hence, there is not such a freedom for the solution of the optimization problem (mainly if there are not so many actuators in the HVAC system). By contrast, for thermal comfort classes B and C, the issues with the optimization problem freedom do not appear and P3 shows the energy savings potential compared to P2 for these classes.

Note also that P1 control strategy is unable to keep temperature in the desired ranges for class A and hence consumes

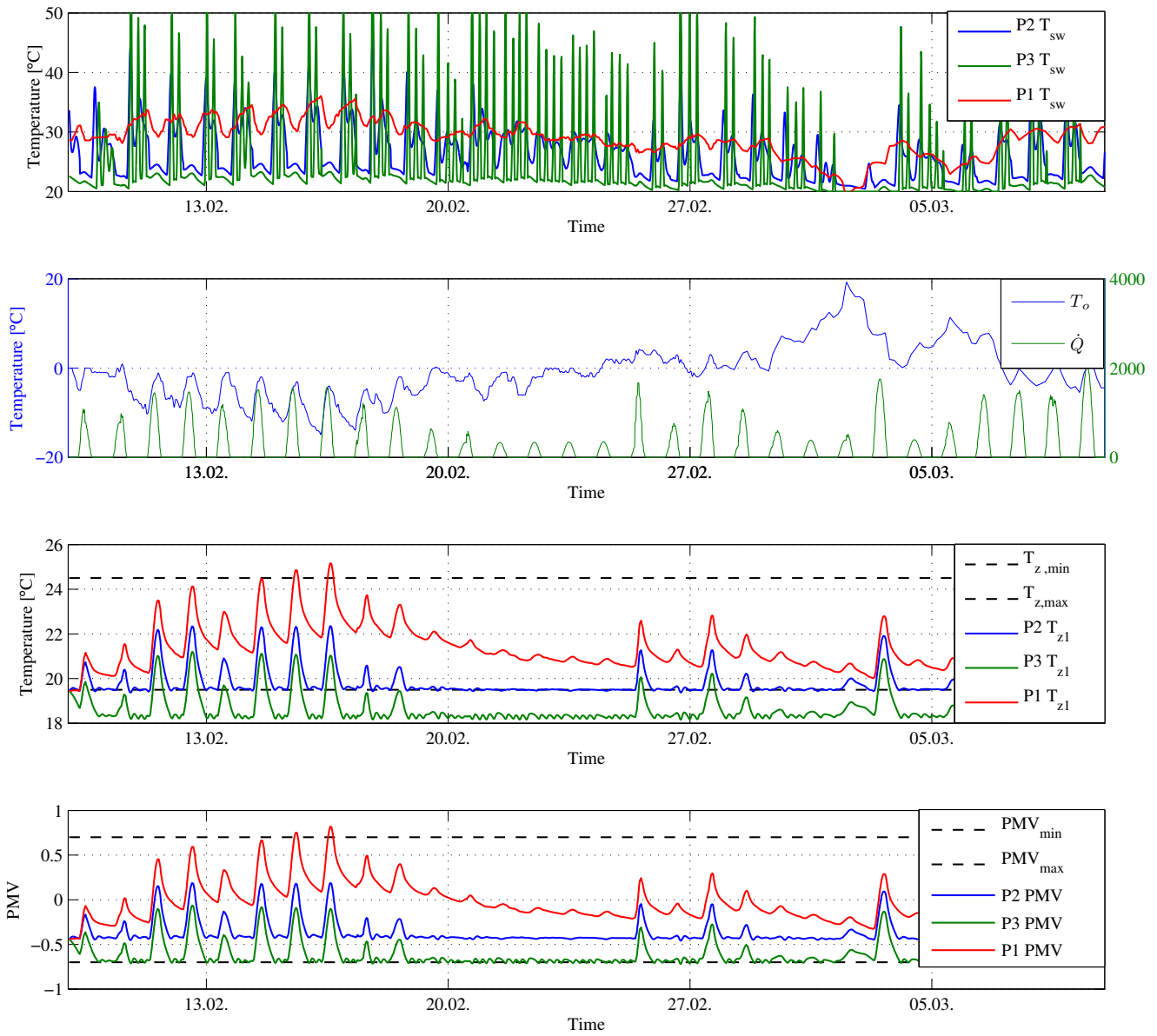


Fig. 2. Timeseries for all control strategies, thermal comfort class C, signals for the first zone only.

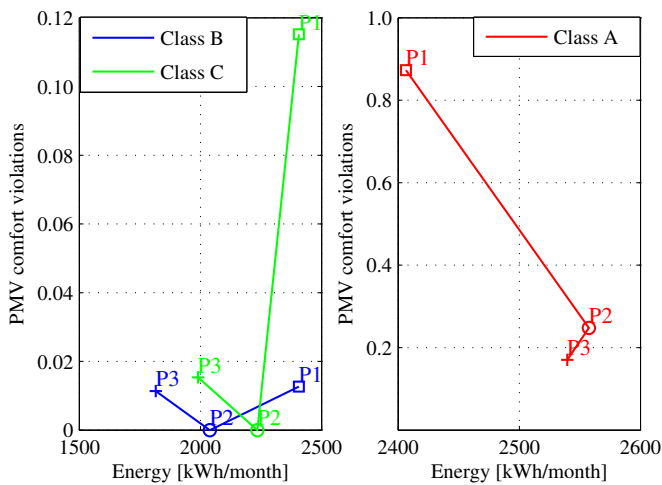


Fig. 3. Consumed energy and comfort violations in terms of the average of PMV range violation.

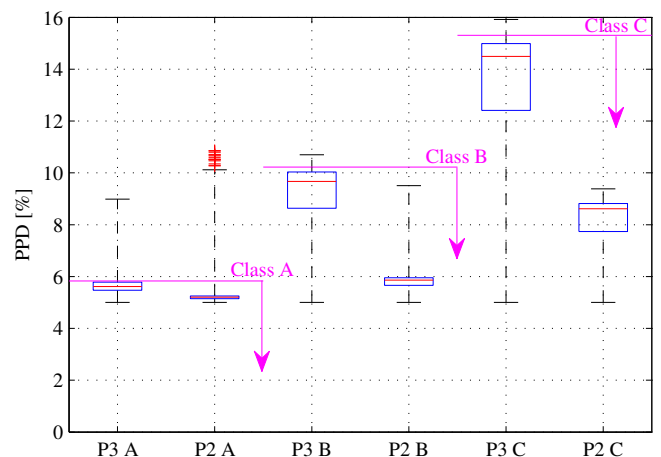


Fig. 4. Box plot showing the predicted percentage of dissatisfied, magenta line shows the limit defined by a particular thermal class.

TABLE IV
COMPARISON OF THE COMPUTATIONAL DEMANDS^a

Prediction horizon	P2 (convex)	P3 (nonconvex)
$N = 8$	0.38 s	3.07 s
$N = 16$	1.07 s	61.06 s
$N = 24$	1.18 s	324.72 s
$N = 32$	2.05 s	969.63 s

^a(recorded on Debian Linux 6.0.3 machine with two processor cores at 2.60 GHz)

the smallest amount of energy within the elaborated set. For the remaining thermal classes, it evinces worse behavior from both the thermal comfort and the energy point of view.

Finally, P2 and P3 were compared from the computational times point of view. Table IV summarizes the computational time needed to compute respective problems for different prediction horizons. The non-convexity of the problem P3, however, limits its applicability.

VI. CONCLUSION AND FUTURE WORKS

A. Conclusion

Further possibilities for energy cuts have been shown. The proposed approach relies on the reserves in the thermal comfort. By optimizing the thermal comfort index PMV directly, predictive control approach can save further 11 % energy compared to the classical MPC formulation while keeping the comfort within the range defined by standards.

Inclusion of PMV into the cost function and constraints, however, brings about some issues:

- The resulting optimization problem is nonlinear and therefore, for large setups, difficult to solve. Prediction horizon of two hours was considered for the presented simulations, nonetheless, for a longer prediction horizon, the problem becomes intractable (see Table IV). Such a prediction horizon is short for buildings with a huge thermal mass because the control system is unable to react in advance to abrupt changes of disturbances, which usually results in pre-cooling effects, etc. (see also Fig. 2 and discussion in Section V).
- The prior knowledge of the activity of the occupants, clothing, etc. is assumed. Therefore, the temperature range in the standards is more strict than PMV range. However, air and mean radiant temperature belong among the dominant factors influencing the comfort index. The rest of the quantities in the PMV formula does not have such a huge impact and thus an expert estimate is sufficient.

B. Future Works

The tractability of the proposed optimization problem is crucial. Scalability of the proposed problem can be achieved by a convex approximation of the given optimization problem. This can be done using reformulation of the problem into lifted variables and a conversion to a semi-definite program. It was shown that PMV based formulation has a wider range of operational temperature to work with therefore an adaptive temperature trajectory within the classical MPC formulation is also an option. Having an approximation

algorithm, the prediction horizon can be extended in order to incorporate more information about future disturbances and thus obtain better control performance as well as lower peaks in the manipulated variables (as they are in Fig. 2).

VII. ACKNOWLEDGMENTS

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