SIMULATION-ASSISTED SPACE COOLING IN EXISTING BUILDINGS: A CASE STUDY

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ABSTRACT

The implementation of predictive control approach for passive cooling in an existing, heritage protected office building is described. Thereby, control options (alternative positions of windows, shades, etc.) are proactively simulated (using weather forecast data for the next 24 hours) and evaluated to identify the option with the most desirable performance.

INTRODUCTION

The combination of relatively low energy prices, increasing user demands and low costs for active cooling devices led to spread of energy-intensive mechanical systems for space cooling technologies particularly in areas with moderate climate. However, recent ecological and economical developments (e.g., climate change, urban heat island effect, energy prices) have brought about, amongst other things, a renewed interest in energy-efficient alternative for building controls. The intelligent use of passive cooling methods combined with innovative materials as well as advance sensory and actuating components and building control has the potential to significantly decrease the energy consumption for space cooling (Lomas 2006). Instances of this approach have been implemented in new build structures in the last years in different climate zones (e.g. Krausse et al. 2007; Salmeron et al. 2009).

The usage of natural ventilation in buildings has a long history. Many recently constructed buildings focus on the use of natural ventilation (e.g.: San Francisco Federal Building by Morphosis; Garça et al. 2003). The principle possibility to combine natural ventilation and building controls in existing buildings was presented in previous publications (Mahdavi & Pröglhöf 2004, 2005, and 2006; Mahdavi 2008).

The present contribution focuses on the integration of a novel predictive control approach (Mahdavi et al. 2009) using passive cooling technologies in an existing office building. The objective is to provide appropriate indoor conditions while operating in a sustainable manner. For implementation an existing heritage-protected university building in Vienna, Austria, was chosen (Pröglhöf et al. 2010). The following measures were considered: i) natural (mostly night-time) ventilation using windows equipped with software-controlled actuators, ii) solar control via shading devices equipped with actuators, iii) thermal mass, iv) phase change materials (PCMs), and v) ceiling fans. These measures were integrated within a novel systems control context that deploys a predictive (simulation-assisted) strategy.

METHODS

Three similar south oriented offices in a building of our university campus were selected (Figure 1) for our study. The building with its walls out of brick and wooden ceilings is typical for Vienna and its heritage protected structures. The selected rooms are referred to as R1, R2 and R3. R1 was left untouched and used as reference room. The room is equipped with manual internal, low quality venetian blinds. The users can open the windows manually. In R2 and R3 the existing windows have been partly motorized. R2 was equipped with automated internal venetian blinds and R3 with automated external venetian blinds (Figure 2). In R3 PCMs and a ceiling fan were installed in addition (Figure 3).

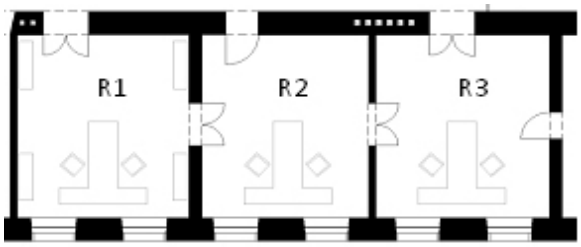

Figure 1 Floor plan of the three offices

Figure 2 Windows and shades of R3

Figure 3 Ceiling fan and suspended ceiling with PCM in R3

Additionally sensors were installed to measure indoor and outdoor environmental data. Outdoor environmental data is collected by sensors mounted at the façade (air temperature, relative humidity, wind speed, and precipitation) in front of the offices. Additional data is collected by a weather station on the rooftop (global horizontal radiation, and diffuse horizontal radiation). All rooms were equipped with sensors for measuring air, globe, and surface temperature, humidity, illuminance at the ceiling and at the workplace, CO2, and flow velocity. Occupancy, shade position and door/window status were also monitored (Figure 4). R2 and R3 are run by a novel, predictive building control system, which controls the building based on weather forecast and thermal simulation. The users can overrule the control system using a graphical user interface (GUI) and directly control windows, shades and the ceiling fan (Figure 5).

Figure 4 Workplaces in R2 with motorized window, internal venetian blinds and sensors

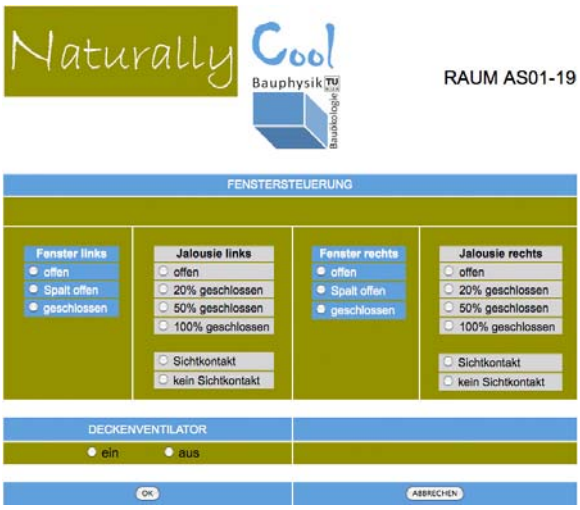

Figure 5 Graphical user interface for R3

The user interface was implemented in the programming language PHP to reach platform independence. The room controller handles all actors, conventional building sensors as well as high accuracy measurement equipment. The comunication is realized via Ethernet/IP.

The novel idea is not to react to sensor data in a control loop, but to simulate the building performance using weather forecast and control scenarios to determine the most favorable scenario and run the building in this mode in the next control loop. Figure 6 depicts the data flow of the predictive control scheme.

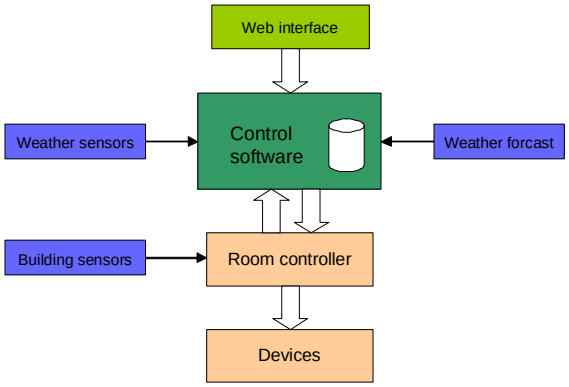

Figure 6 Dataflow diagram for the predictive control scheme

First an exploratory test was conducted in two rooms using fixed control rules (instead of simulations) to learn how the building reacts and how the three differently equipped rooms perform. In this phase the windows opened fully when the indoor air temperature θ_i was higher than the outdoor air temperature θ_{out}, under the condition that the indoor air temperature θ_i was >20 °C. The shades were deployed 80% when a certain vertical illuminance level (5000 lx) was reached at the façade. Based on

these experiences the simulation model could be calibrated to a satisfying level as exemplarily shown in Figure 7, where the simulated indoor air temperature $\theta_{i,sim}$ for R3 is compared with the measurements.

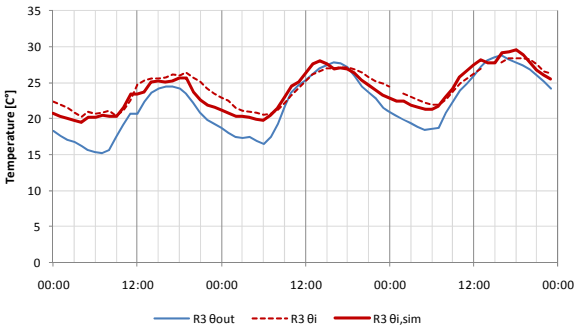

Figure 7 Comparison of the predictions of the calibrated simulation application for R3 over the period of three days in August 2009 with corresponding measurements

In a next phase the predictive control (Mahdavi et al. 2009) was implemented. Thereby, two sets of tests were performed as follows:

Predictive control I. Based on weather forecast data, various alternative control scenarios are computed using the above mentioned simulation model (Orehounig et al. 2010). The simulation results are then used ot rank these alternative control scenarios for window and blind operation are ranked according to the simulation results. The best performing control scenario is selected as the preferable control strategy for the next control period (24 hours).

As benchmark indicator the mean overheating OH_m of the indoor air temperature during working hours (8:00-18:00) was established (Equation 1). The hourly indoor air temperature θ_i (in °C) subtracted by the reference indoor air temperature θ_r (=26°C) divided by the number of considered hours (n=10) is summed up for one day. The term θ_i - θ_r in Equation 1 is considered for those hours when $\theta_i > \theta_r$, otherwise the term is set zero.

$$OH_m = \sum_{j=1}^{n} \frac{\theta_{i,j} - \theta_r}{n} \qquad (1)$$

As simulation tool EDSL Tas (EDSL 2008) was used to simulate the various alternative scenarious every twentyfour hours. The above described method was first tested in the summer of 2009.

Predictive control II. A second test of the approach was conducted in June 2010. Thereby, a different simulation engine was adopted (HAMBase, van Schijndel 2007) and integrated in a MatLab-routine. A genetic algorithm is used to generate best performing control scenarios based on simulation results. This scenarios are evolved every hour. The method uses extrem (e.g. all windows open; shades fully deployed) and randomly chosen initial settings for all actuators, as the starting point toward computing internal conditions for the next 24 hours. The genetic algorithm uses the results to optimize the scenarios (Schuss et al. 2010).

Parallel to system operation, users in the offices were interviewed to obtain their evaluations of the indoor conditions and the operation of the systems.

RESULTS AND DISCUSSION

Exploratory test results

Results of the first exploratory test are shown in the next figures. Figure 8 shows the resulting indoor air temperatures θ_i in all three offices, together with the outdoor air temperature θ_{out}. While the outdoor air temperature increases day by day, R3 (best equipped) tends to resist the overheating better than R2 (less equipped), followed by R1 (reference room).

The average surface temperature of the rooms $\theta_{s,room}$, are compared in Figure 9. The surface temperatures for the rooms and the PCMs is measured at three different points and averaged. Again the performance of R3 leads to cooler temperatures than in the other two rooms. In terms of room surface temperatures R1 performed better than R2.

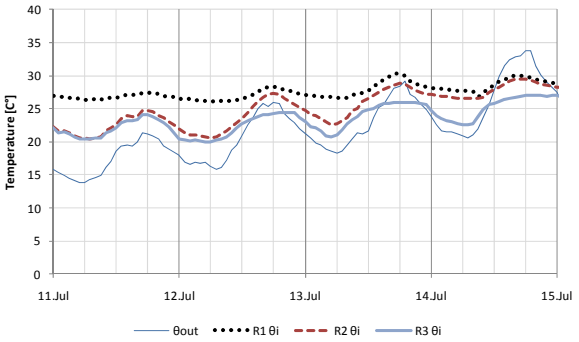

Figure 8 Comparison of the indoor air temperatures θ_i in the three office rooms (R1-3)

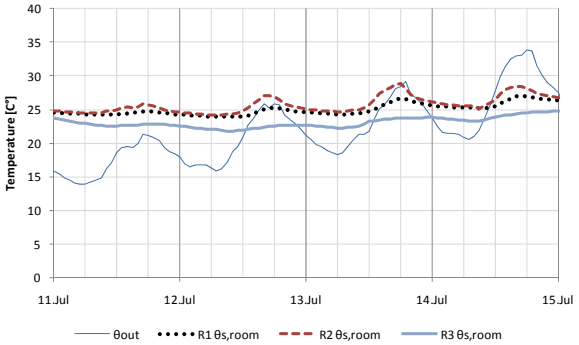

Figure 9 Comparison of the average surface temperatures ($\theta_{s,room}$) in the three office rooms

The development of indoor air (θ_i), averaged room surface ($\theta_{s,room}$) and averaged PCM surface temperatures ($\theta_{s,pcm}$) in R1 over the mentioned three day period of increasing outdoor air temperature are shown in Figure 10.

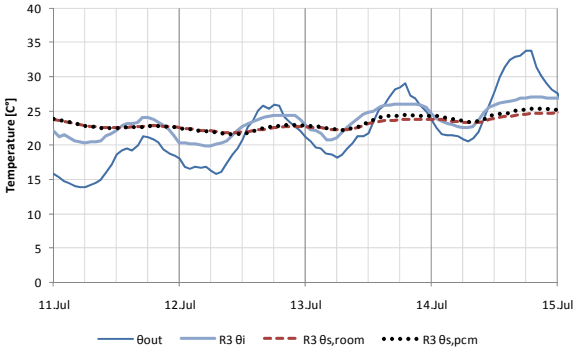

Figure 10 Development of outdoor and indoor temperatures in R3 over a three day period of increasing external temperature

Predictive control I

The weather forecast for the outdoor air temperature $\theta_{out,forecast}$, basis for the predictive control approach, is exemplarily shown in Figure 11 and compared with the measured outdoor air temperatures θ_{out} over a period of three days. To get these predictions, web based services are used. This is the reason why there is a difference between the measured value and the starting value of the prediction at 18:00. Although the prediction is renewed every 24 hours at 18:00 the forecast shows no obvious jumps between the single days.

To illustrate the operation of the system, we focus here on four scenarios (amongst the set of scenarios considered) with different schedules for window position and shade deployment. These scenarios are described in Table 1 (Orehounig et al. 2010). Thereby, "0" deontes window closed or shade not deployed, whereas 1 denotes window/shade fully open/deployed. Figure 12 shows, for these scenarios, the predicted indoor temperatures in R3.

The scenario showing the least mean overheating OH_m of the indoor air temperature during working hours was then chosen. The indoor air temperatures, resulting out of the predictive control strategy, are presented in Figure 13 for all three offices over a period of one week. The effect of natural ventilation during the night time can be seen in the performance of the indoor air temperature in R2 and R3. In questionaires, users in R2 and R3 assessed the air temperature in the offices in times with predictive control cooler than without. Nighttime ventilation as well as the additional shading devices, and the possibility to control the devices with the GUI were explicitly rated positive.

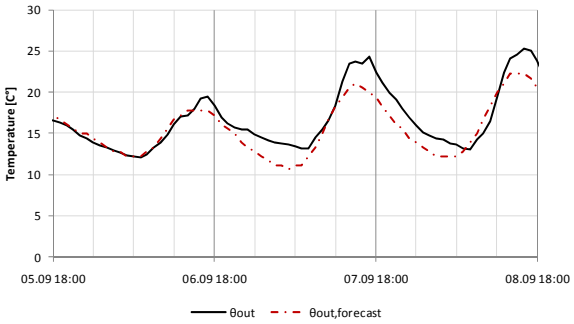

Figure 11 Comparison of the daily 24 hour outdoor air temperature forecast with the measured outdoor air temperature values

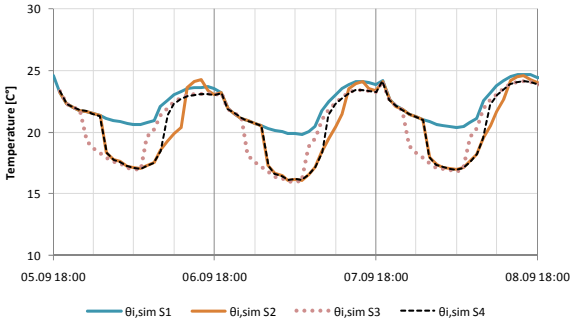

Figure 12 Simulation results of four control scenarios for indoor air temperature ($\theta_{i,sim}$) in R3

Table 1
Illustrative alternative control scenarios (s1 to s4)

	S1		S2		S3		S4	
hour	w	sh	w	sh	w	sh	w	sh
19:00	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
20:00	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
21:00	0.4	0	0.4	0	0.4	0	0.4	0
22:00	0.4	0	0.4	0	1	0	0.4	0
23:00	0.4	0	0.4	0	1	0	0.4	0
00:00	0.4	0	0.4	0	1	0	0.4	0
01:00	0.4	0	1	0	1	0	1	0
02:00	0.4	0	1	0	1	0	1	0
03:00	0.4	0	1	0	1	0	1	0
04:00	0.4	0	1	0	1	0	1	0
05:00	0.4	0	1	0	1	0	1	0
06:00	0.4	0	1	0	1	0	1	0
07:00	0.4	0	1	0	0.4	0	1	0
08:00	0.4	0	1	0	0.4	0	1	0
09:00	0.4	0	1	0	0.4	0	1	0
10:00	0.4	0.8	1	0	0.4	0.8	0.4	0.8
11:00	0.4	0.8	1	0	0.4	0.8	0.4	0.8
12:00	0.4	0.8	1	0	0.4	0.8	0.4	0.8
13:00	0.4	0.8	0	0.8	0.4	0.8	0.4	0.8
14:00	0.4	0.8	0	0.8	0.4	0.8	0.4	0.8
15:00	0.4	0.8	0	0.8	0.4	0.8	0.4	0.8
16:00	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
17:00	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8
18:00	0.4	0.8	0.4	0.8	0.4	0.8	0.4	0.8

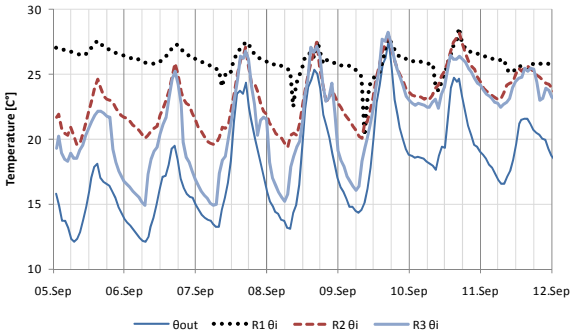

Figure 13 Performance of air temperatures θ_i as result of predictive control in all three offices over the period of one week

Predictive control II

Figure 14 shows the simulated inoor air temperature ($\theta_{i,sim}$) for R3 and all scenarios for the next 24 hours. Hour 0 corresponds to the time when simulations were executed (in this case, at 20:00). The best performing scenario is plotted black and the related window and shade position is highlighted.

Figures 15 and 16 show the temperature ($\theta_{i,sim}$) for R3 one and two hour later respectively. Again the results of all scenarios for the next 24 hours (calculated at 21:00 = 0 hours and 22:00 = 0 hours). As input for this prediction the history of the measured values (last 24 hours) for outdoor air temperature θ_{out} and indoor air temperature θ_i is used (left part of the graphs).

These three Figures show, that the best performing scenario is recomputed on an hourly basis.

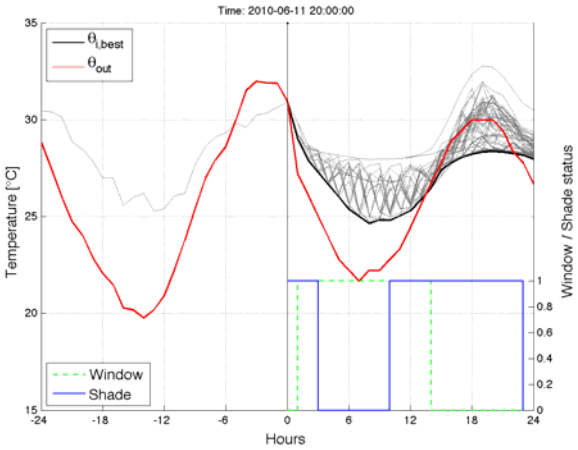

Figure 14 Temperature for R3 ($\theta_{i,sim}$), simulations conducted at 20:00

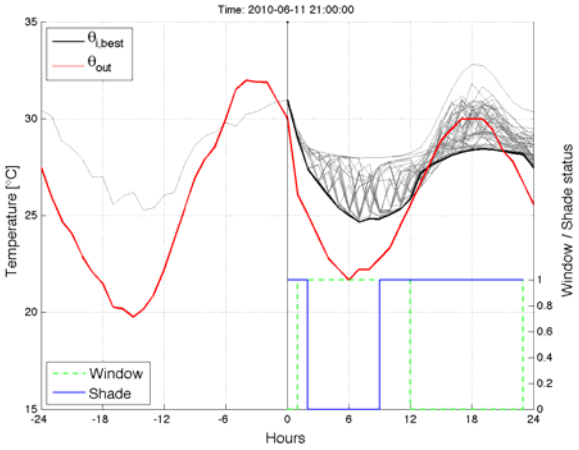

Figure 15 Temperature for R3 ($\theta_{i,sim}$), simulations conducted at 21:00

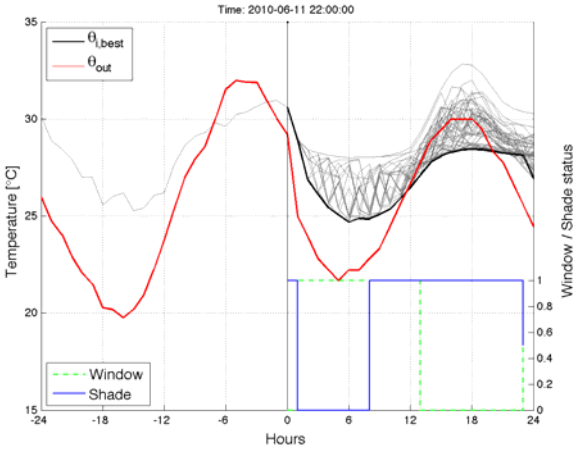

Figure 16 Temperature for R3 ($\theta_{i,sim}$), simulations conducted at 22:00

CONCLUSION

The implementation of the predictive control started in 2009 and was reintatiated for the summer of 2010. Results to date are promising, in the sense that the feasibility of the approach is clearly demonstrated. Given reliable simulation models (with calibrated input assumptions and boundary conditions), the approach reliably identifies preferable control options. Ongoing research addresses, amongst other issues, users' impact on the system's performance, particularly whenever users have the oppurtunity – as they should – to overrule systems settings and recommendations.

ACKNOWLEDGEMENT

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