A SIMULATION-SUPPORTED CONTROL SCHEME FOR NATURAL VENTILATION IN BUILDINGS

Ardeshir Mahdavi, Kristina Orehounig, Claus Pröglhöf
Department of Building Physics and Building Ecology
Vienna University of Technology
Vienna, Austria

ABSTRACT

This paper addresses the potential of the simulation-assisted operation of devices for natural ventilation.
Toward this end, a control scheme was conceived as follows: at specific points in time, the control system applies simulation to predict how various window operation regimes would affect the indoor temperature in the building over the course of the following day. Comparison and ranking of the simulation results is conducted using Mean Overheating of the indoor air in selected spaces as the relevant performance indicator. The approach was virtually implemented in two reference buildings, suggesting its potential toward predictive identification of a favorable course of action in operating devices for natural ventilation.

INTRODUCTION

This paper reports on the recent results of a long term research effort toward the implementation of a simulation-based approach for the operation of indoor environmental control systems in buildings (Mahdavi 2008). Specifically, it addresses the potential of the simulation-assisted operation of devices for natural ventilation.
The control system in the respective scenario possesses an internal digital representation consisting of room, weather, and occupancy models. The room model entails information about building geometry and components, as well as the position of virtual sensors that monitor pertinent performance parameters such as room air temperature and relative humidity. The weather model is supplied with real-time weather station data.
To maintain the desired performance under dynamically changing internal and external conditions, simulation-based control system operates as follows (see Figure 1):

i) At regular time intervals, the system considers a set of candidate control states (i.e., a set of alternative combinations of the states of control devices such as opening degree of windows) for the subsequent time step.

ii) These alternatives are then virtually enacted via numeric simulation, resulting in values for corresponding performance indicators such as indoor air temperature.

iii) The results are compared and ranked according to the preferences (objective function) specified by the occupants and/or facility manager to identify the candidate control state with the most desirable performance.

iv) The system either autonomously instructs the pertinent control device-actuator(s) or informs the user to adjust the control state.

We examined the potential of this approach toward simulation-assisted control of window positions in two reference buildings. The idea was to utilize the day-night difference in outdoor air temperature toward passive space cooling via optimized dynamic operation of windows. Thereby, a simulation-supported predictive control scheme was conceived and implemented toward comparison and ranking of the consequences of various control options. Mean Overheating (of the indoor air in selected spaces) was used as the relevant performance indicator.
To address the implications of weather forecast errors on the reliability of the control system, simulations were repeated under deviating weather forecast scenarios, involving various degrees of errors. Results to date suggest that, the system's original ranking of the control options remained mostly valid, suggesting that the relative ranking of control options (ranking matrix) in a simulation-based systems control scenario may be somewhat resilient in the face of moderate weather forecast errors. Moreover, in a real system operation scenario, parametric simulations can run on a continuous basis, allowing thus for regular readjustment of weather forecast data and, in case necessary, for revision of recommended control actions.

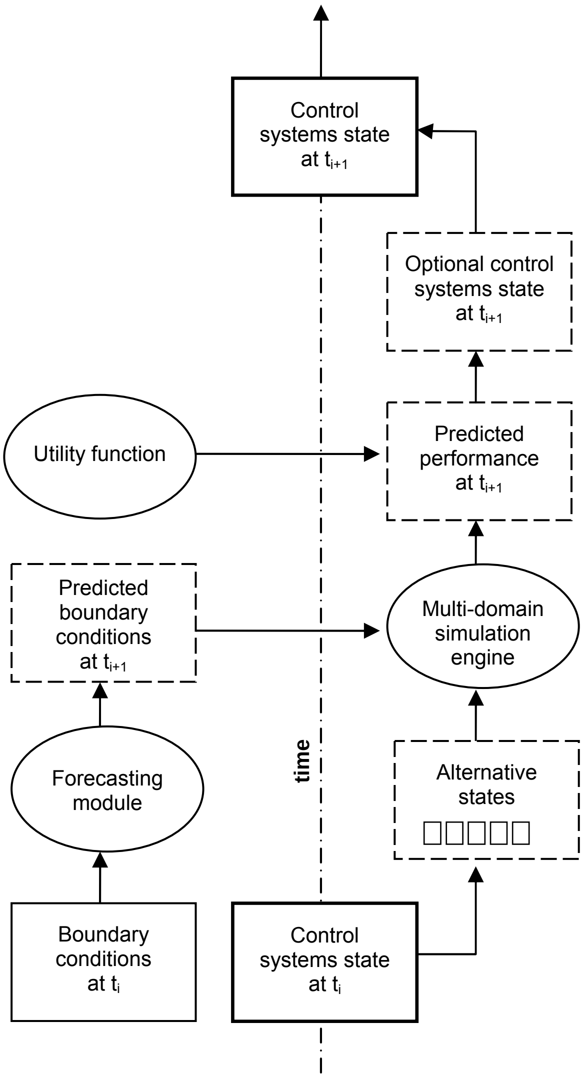

Figure 1 The schematic illustration of the simulation-assisted building systems control strategy

APPROACH

The potential for the application of a simulation-based natural ventilation control strategy has been addressed, in principle, in our previous publications (Mahdavi and Pröglhöf 2005, 2004). In a recent simulation study, we further explored the possibility of simulation-assisted predictive control schemes for window operation in two reference buildings, namely an office building (see Figures 2, 3) and an apartment (see Figures 4, 5).

The office building

Concerning the office building, we used the information collected in a previous research project (Mahdavi 2007). Thereby, a number of rooms were selected in a building in Hartberg, Austria (Figure 2, 3). All selected offices face northeast. Windows are equipped with external, manually operated shades as well as curtains. The offices are naturally ventilated via operable ("tilt and turn") windows.

We monitored external weather conditions and indoor climate (in 6 offices on the 1st and 2nd floors of this building) continuously over a period of eight months. Moreover, we also monitored occupancy as well as user control actions (lighting, shading, and window operation).

The apartment

The second reference object is a small (two-room) apartment in the lower level of a typical residential building in Vienna, Austria (Figures 4, 5). As with the office building, indoor environmental measurements (temperature, humidity, illuminance) were performed in this object over a period of six weeks. The apartment's windows ("tilt and turn" units) are manually operated. Windows are equipped with manually operated internal shades.

Figure 2 External view of the selected office building

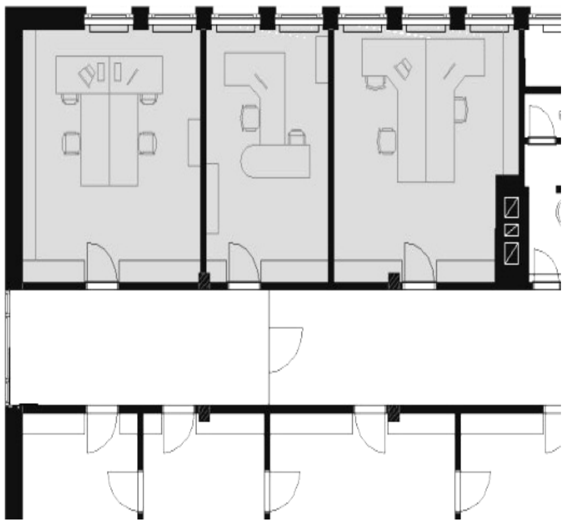

Figure 3 Plan of the selected rooms in the reference office building

Figure 4 External view of the selected apartment

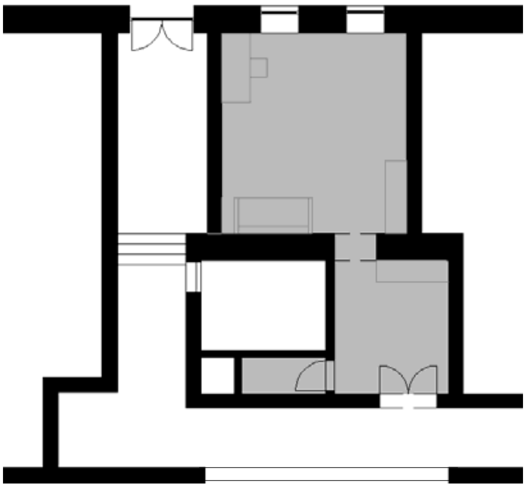

Figure 5 Plan of the selected rooms in the reference apartment

Calibration

Given general building information (geometry, construction), local weather station data, as well as information on user presence and control actions (resulting in specific window opening positions), we modeled the thermal performance of the above mentioned buildings. Using measured indoor data (room air temperature), the applied numeric simulation application (EDSL 2008) could be calibrated resulting in a satisfactory agreement between measured and predicted indoor conditions. This software tool simulates dynamically the thermal performance of buildings and their systems. The application solves the sensible heat balance for a zone by setting up equations representing the individual energy balances for the air and each of the surrounding surfaces. These equations are then combined with further equations representing the energy balances at the external surfaces, and the whole equation set is solved simultaneously to generate air temperatures, surface temperatures and room loads. Conduction in the fabric of the building is treated dynamically using two methods for the analysis of wall heat flows. For state-representation finite difference methods are applied whereas conductive heat flows at the surfaces of walls and other building elements are calculated with response factor method. Convection is treated using a combination of empirical and theoretical relationships. Long-wave radiation exchange is modelled using the Stefan-Boltzmann law. Long-wave radiation from the sky and the ground is treated using empirical relationships (EDSL 2007).

Control scheme

Using the calibrated simulation models, we examined the potential of a simulation-assisted control of window positions in the above mentioned buildings (one room in each object). The idea was to utilize the day-night difference in outdoor air temperature toward passive space cooling via optimized operation of natural (window) ventilation. Toward this end, a control scheme was conceived as follows:

At a specific point in time in a typical summer day (d_j), the control unit applies simulation to predict how various window operation regimes would affect the indoor temperature in a building over the course of the following day (d_{j+1}). An "operation regime" denotes in this context which windows, when, how long, and to which extent, are opened.

Performance indicator

To compare and rank the performance of various control options (alternatives), we applied the Mean Overheating (OH_m) of the indoor air in selected spaces (see Eq. 1) as the relevant performance indicator.

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

Where θ_i denotes indoor air room temperature (^oC) at hour i in day d_{j+1}, θ_r the reference indoor air temperature for overheating (^oC), and n the total number of considered hours in day d_{j+1}. This number was considered to be 10 for the office building (from 7:00 to 17:00) and 24 for the apartment. Note that the term $\theta_i - \theta_r$ (in Eq. 1) is considered only for those hours when $\theta_i > \theta_r$. In our illustrative example, the reference overheating temperature (θ_r) was assumed to be 26 ^oC for the office building and 27 ^oC for the apartment.

Illustrative control options

In an actual control situation, the weather forecast information for the following day is used as input information for the simulation runs. Thus, amongst a number of discrete alternative window operation scenarios, one could be selected, which, according to simulation results, would minimizes the overheating of the indoor air in the following day. To illustrate

this process, Table 1 and 2 show (for the office and apartment objects respectively) a number of alternative window operation scenarios (schedule and degree of window opening).
Note that, in these examples, the scenario S0 involves no shades deployment, whereas window shading schedule was identical in the other scenarios. In the case of the office building, shades were deployed during the day (from 6:00 to 18:00) and were retracted over the night (18:00 to 6:00). In the case of the apartment, shades were assumed to be closed between 20:00 in the evening to 14:00 in the following day.

Table 1
Illustrative alternative control scenarios considered for window operation (opening degree in %) during day (from 6:00 to 18:00) and night (from 18:00 to 6:00) in the selected office (window shades in scenarios S1 to S6 are deployed from 6:00 to 18:00)

Scenario	Window opening degree in %		Shading
	6:00 to 18:00	18:00 to 6:00	
S0	3	1	No
S1	3	1	Yes
S2	30	1	Yes
S3	30	30	Yes
S4	10	10	Yes
S5	10	30	Yes
S6	3	30	Yes

Table 2
Illustrative alternative control scenarios considered for window operation (opening degree in %) during day (from 8:00 to 24:00) and night (from 24:00 to 8:00) in the selected apartment (window shades in scenarios S1 to S7 are deployed from 20:00 to 14:00)

Scenario	Window opening degree in %		Shading
	8:00 to 24:00	24:00 to 8:00	
S0	35	1	No
S1	35	1	Yes
S2	35	8	Yes
S3	35	35	Yes
S4	8	8	Yes
S5	8	35	Yes
S6	1	35	Yes
S7	1	60	Yes

RESULTS

Calibration

As previously noted, the predictions of the simulation applications were compared with measurements toward calibration of the simulation models for the two reference buildings. To demonstrate this point, Figure 6 shows, as an example, the simulated and measured indoor air temperature in the office for three days in May 2006, together with outdoor temperature (θ_e). A similar comparison of measured and simulated indoor air temperatures for the apartment building are shown in Figure 7, based on data collected in the course of 3 days in July 2008. The relationship between measured and simulated indoor air temperatures for the latter object is further illustrated in Figure 8.

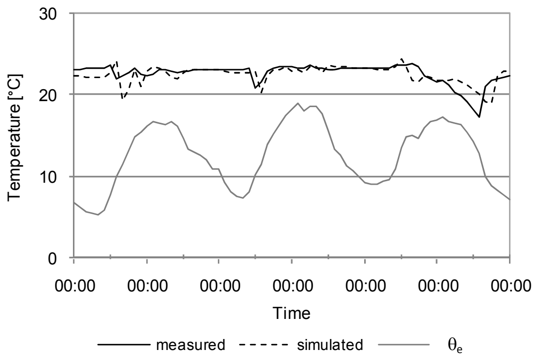

Figure 6 Comparison of the predictions of the calibrated simulation application for the office (indoor temperature in an office over the course of 3 days) with corresponding measurements

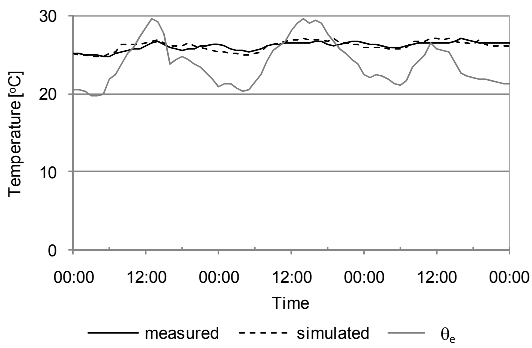

Figure 7 Comparison of the predictions of the calibrated simulation application for the apartment (indoor temperature over the course of 3 days) with corresponding measurements

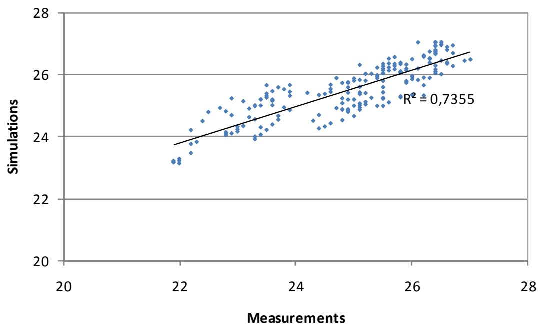

Figure 8 The relationship between measured and simulated indoor air temperature in the apartment building based on data for a period of 8 days

Control decisions

Figure 9 shows the simulation-based predictions of the indoor air temperature in the selected office over the course of a day (d_{j+1}) for various control options as summarized in Table 1. Likewise, Figure 10 shows the simulation-based predictions of the indoor air temperature in the selected apartment over the course of a day (d_{j+1}) for various control options as summarized in Table 2. Figures 9 and 10 include also the respective values of outdoor temperature (θ_e).
Table 3 shows the predicted OH_m values for each scenario in the case of the office building. Table 4 shows the predicted OH_m values for each scenario in the case of the apartment.
The information in these tables provides a basis for proactive control decision making concerning the proper operation of windows toward an optimized passive cooling strategy using night-time ventilation.

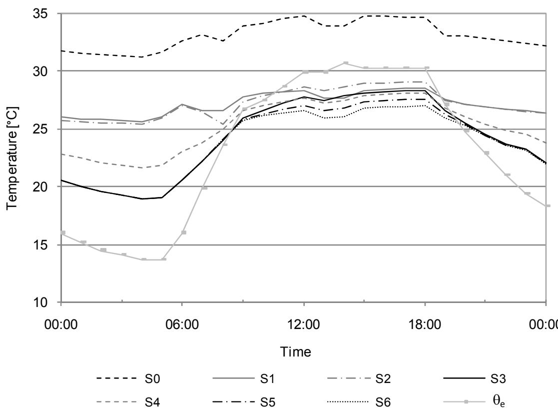

Figure 9 Simulation-based predictions of the indoor air temperature in an office (day d_{j+1}) for alternative control scenarios (1 to 6 as per Table 1) together with outdoor temperature (θ_e)

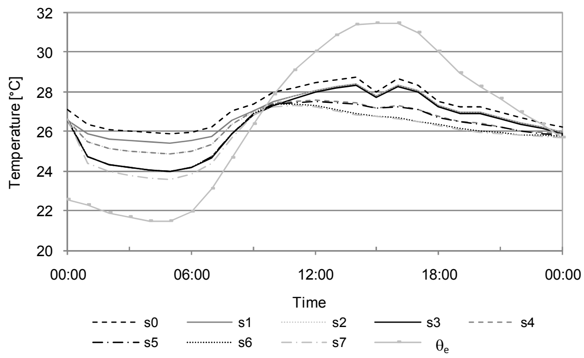

Figure 10 Simulation-based predictions of the indoor air temperature in the apartment (day d_{j+1}) for alternative control scenarios (1 to 7 as per Table 2) together with outdoor temperature (θ_e)

Table 3
Ranking of control scenarios (day/night window opening degrees as shown in Table 1) based on predicted Mean Overheating (OH_m) in K

	OH_m [K]	Rank
S0	7.40	7
S1	1.50	6
S2	0.80	5
S3	0.39	2
S4	0.70	4
S5	0.38	1
S6	0.43	3

Table 4
Ranking of control scenarios (day/night window opening degrees as shown in Table 2) based on predicted Mean Overheating (OH_m) in K

	OH_m [K]	Rank
S0	0.52	8
S1	0.37	7
S2	0.36	6
S3	0.34	5
S4	0.15	4
S5	0.12	3
S6	0.05	2
S7	0.04	1

Weather forecast

Note that in these illustrative examples, the simulation-assisted control functionality was merely emulated. As a consequence, predictions of the thermal conditions (indoor air temperatures) were not based on real-time weather forecast, but conducted using a weather file of the building's location. Thus, weather forecast errors and their implications for the ranking of the options were not considered.
To start addressing this issue, we repeated the simulations (for the apartment building case) under deviating weather forecast scenarios (see Figure 11), involving various degrees of errors (e.g., a deviation

of 1 to 1.5 K in outdoor temperature and 10% in wind speed and global horizontal irradiance). Specifically, we examined two deviating weather forecast variations in each case, one involving and overestimation of the temperature and irradiance values, and one involving an underestimation of these values (cp. Figure 11). Despite these deviations, the system's original ranking of the control options (see Table 4) remained valid also for the alternative weather forecasts. Figure 12 shows, as an example (scenario S4), the changes in the course of the predicted indoor air temperature due to alternative weather predictions.

Though far from a proof, this result suggests that the relative ranking of control options (ranking matrix) in a simulation-based systems control scenario may be somewhat resilient despite moderate forecast errors. Moreover, as noted already in the introduction, in a real system operation scenario, parametric simulations can run on a continuous basis (for example, every hour). This allows for regular readjustment of weather forecast data and, in case necessary, for the revision of the recommended control actions.

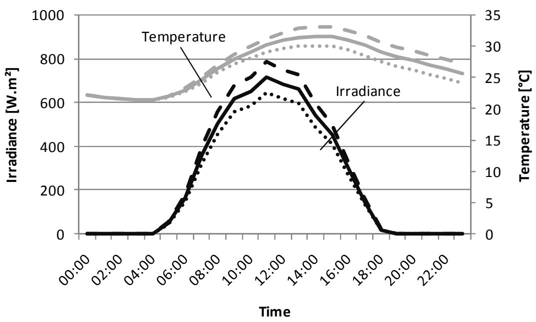

Figure 11 The original weather forecast (regarding outdoor air temperature and global horizontal irradiance) together with two alternative forecast scenarios

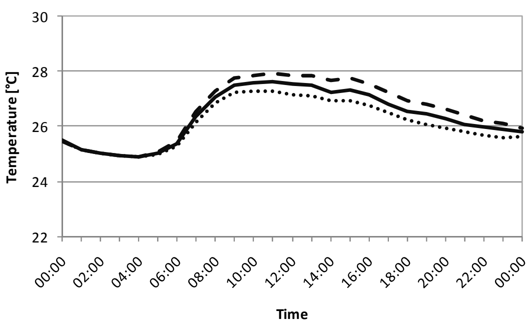

Figure 12 Simulation-based predictions of indoor air temperature in the reference apartment building (day d_{j+1}) for scenario S4 (Table 2 and 4) under the assumption of the original as well as two deviating weather forecasts

CONCLUSIONS

We demonstrated an instance of a computational emulation of a simulation-based control strategy in the natural ventilation domain using two reference objects (an office building and an apartment). Thereby, we demonstrated how a thermal simulation application can be incorporated as an integral component of a building's control system. Given the importance of the timely operation of devices for natural ventilation (particularly in the context of passive cooling strategies), the predictive role of such an embedded simulation capability in the control logic is highly critical.

While the experiences to date underline the promise of the proposed concept, many challenges must be resolved in the course of ongoing and future research and development. Thus, within the framework of an ongoing research effort, a simulation-based window operation system is being implemented in two actual buildings in Austria. Thereby, amongst other issues, the combined effects of inaccuracies due to the simulation algorithms and weather forecast on the reliability of control system recommendations are being studied in an appropriate level of resolutions.

ACKNOWLEDGEMENTS

The research presented in this paper is supported in part by funds from FFG (K-Project: "Multifunctional Plug & Play Façade" as well as the project: "Naturally Cool" Project-Nr: 817575). Additional support was received via "Wirtschaftskammerpreis 2008" (Project: "An innovative energy-efficient and economical room cooling method"). The authors would also like to acknowledge simulation calibration work performed by Mr. Essam Said.

REFERENCES

EDSL 2008. A-TAS Version 8.5. Environmental Design Solutions Limited. www.edsl.net.

EDSL 2007. A-Tas Theory Manual. EDSL Documentation.

Mahdavi, A. 2008. Predictive simulation-based lighting and shading systems control in buildings. Building Simulation, an International Journal. Springer. Volume 1, Number 1. ISSN 1996-3599. pp. 25 – 35.

Mahdavi, A. 2007. People, Systems, Environment: Exploring the patterns and impact of control-oriented occupant actions in buildings. (Keynote) PLEA 2007. Wittkopf, S. & B. Tan, B. (Editors). ISBN: 978-981-05-9400-8; pp. 8 - 15.

Mahdavi, A. & Pröglhöf, C. 2005. A model-based method for the integration of natural ventilation in indoor climate systems operation; in: "Building Simulation 2005, Ninth International IBPSA Conference, Montreal, Canada". pp. 685 - 692.

Mahdavi, A. & Pröglhöf, C. 2004. Natural ventilation in buildings – Toward an integrated control approach. Proceedings of the 35th congress on air-conditioning, heating, refrigerating. (Eds: SMEITS), "AMD Sistern". pp. 93 – 102.