PREDICTIVE MODEL-BASED CONTROL OF VENTILATION, LIGHTING, AND SHADING SYSTEMS IN AN OFFICE BUILDING

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ABSTRACT

This paper reports on ongoing work toward implementing a predictive control approach for buildings systems for ventilation, lighting, and shading. The main objective of this method is the optimized control of multiple devices toward usage of passive cooling and natural lighting. Thereby, control options (various opening positions of windows, shades, etc.) are generated and computationally assessed using a combination of option space navigation via genetic algorithms and numeric simulation.

INTRODUCTION

In the last few years system and energy expenditures for space cooling have dramatically increased, even in central-European climatic zones. This has encouraged the efforts to develop and implement smart (energy-efficient) cooling methods. An intelligent control approach involving all relevant systems and endowed with the capacity of proactive (predictive) control is believed to have the potential to significantly reduce buildings' energy demand. Toward this end, passive cooling, advanced shading control, and increased usage of natural light is essential. Possibilities to use natural ventilation and building controls in existing buildings were presented in previous publications (Mahdavi & Pröglhöf 2004, 2005, and 2006; Mahdavi et al. 2008; Orehounig 2010; Pröglhöf 2010).

This paper further develops a new simulation-based predictive control approach (Mahdavi 2008; Mahdavi et al. 2009) with the capability to facilitate the application of the aforementioned sustainable indoor climate control systems. The core idea behind this approach is the use of numeric building performance simulation applications to predict – ahead of an actual control action – the consequences of multiple control options. Once the options are generated and virtually realized via simulation, they can be evaluated and ranked, thus providing a basis for optimal control decision making.

METHOD

To implement the proposed model-based control strategy a realistic setting is essential. Therefore, we selected two buildings for implementation. This paper focuses on one of these buildings, namely a modern office building ("Fibag") in Stallhofen, Styria, Austria (see Figure 1 to Figure 3). The building has a typical glass and aluminium façade (Figure 1). The primary structure is massive (concrete skeleton, floors, and staircases), but the internal (partition) walls may be described as lightweight.

Two test rooms in this building were selected for experiments. One room was used to test the control approach (see Figure 1 and Figure 3), whereas the second room was used as a reference room. The two test rooms are identical layout-wise and are located in the first and second floor above each other, facing north and east directions. The building is located in a rural, low-density, and low-rise context.

Figure 1. The Fibag Building

Figure 2. The test room

To demonstrate the feasibility of the simulation-based control approach in a multi-system context, sensors and actuators were deployed: The rooms are equipped with programmable room controllers, indoor environmental sensors (Figure 4), as well as actuators for the automated operation of windows (Figure 5) and blinds. Moreover, to monitor local climatic conditions, a weather station (Figure 6) was installed on top of the building.

Table 1 provides a description of all system components. A schema of the test system is illustrated in Figure 4.

Table 1 System components description

SYSTEM COMPONENT	**DESCRIPTION**
Indoor climate sensors	Compact indoor climate stations measuring air temperature, relative humidity and velocity as well as carbon dioxide and radiance
Outdoor climate sensors	Weather station measuring air temperature, relative humidity, precipitation, global irradiance, wind speed and wind direction.
User action and presence sensor	Presence: PIR - Sensor with settable threshold time Door opening: magnetic contact sensors
Window	Two synchronized sleepless settable drives for each window to control the window opening position continually
Shading device	Single drives with a special gear unit for height and angle positioning
Controllable lighting system	The room controller could set on/off and dimming levels between 10-100% of the total lighting power
Backbone and communication network	IP base communication with access to building data points and data history

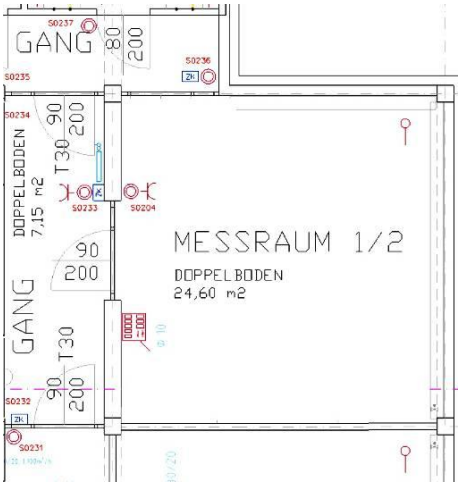


Figure 3. Floor plan of the test room

Figure 4. Internal sensor station

Figure 5. Automated Window

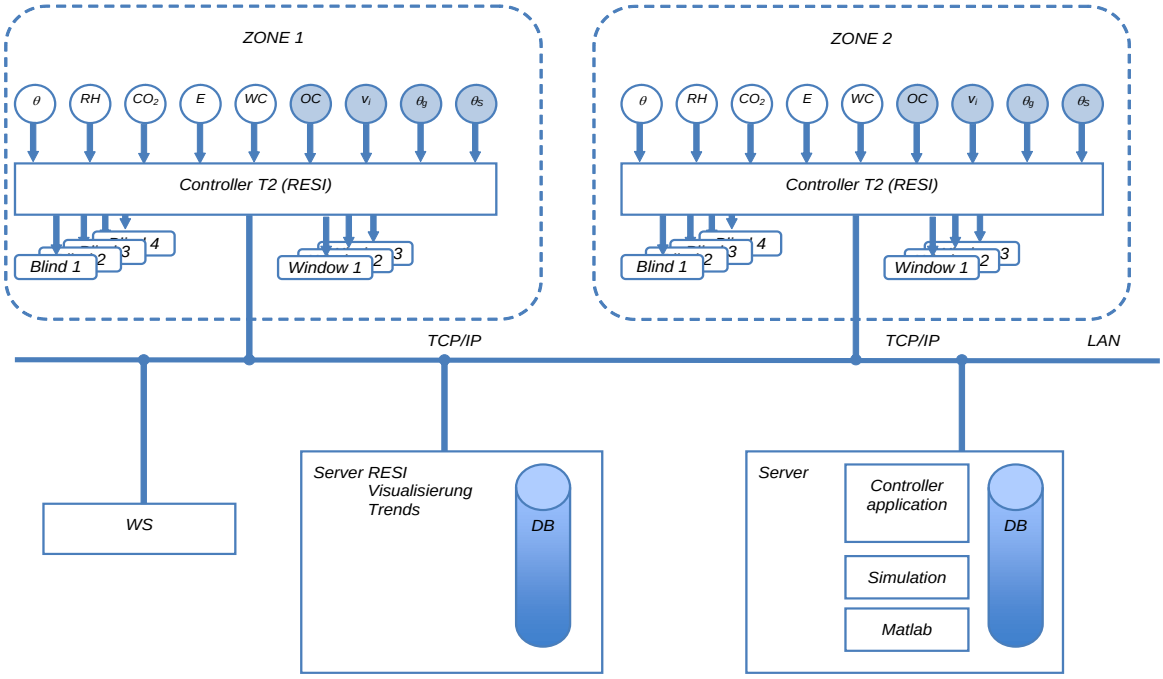


Figure 7. Schema of the test system

Figure 6. Weather station

The aforementioned model-based control approach is being implemented in the test room. Thereby, weather forecast information(Weather.com, 2010) is fed into simulation applications to regularly probe the implications of various control action alternatives in view of desirable indoor-environmental conditions. Thus, the likely optimal course of control action can be identified proactively toward optimization of energy and environmental performance of the building. An essential advantage of the proposed approach is its ability to consider the thermal storage capacity of the building's thermal mass more reliably. In order to better document the performance of the implemented control regime, we will use the second room as a reference room for comparison.

Predictive Control approach

The present paper attempts to further develop the predictive control approach (see Figure 8 and Mahdavi 2008). Instead of the previously applied combination of the greedy search method (combined with stochastic jumps), we know explore the potential of genetic algorithms toward navigation of the control options search space. This modification is necessary, since we would like to be able to generate and evaluate control options on a regular basis (i.e. in short time intervals). Moreover, temporal changes in the position of devices over time (operation schedules) must be considered for each simulation run. These leads to an explosion of the control options (schemes), which could be better tackled via genetic algorithms.

Thereby, weather forecasts (Weather.com 2010) together with expected values required for simulation input (e.g. internal gains) are the starting point for a series of multi-domain simulations (thermal and lighting) based on a genetically produced variation of alternative control states. The control process was implemented in MATLAB (MATLAB 2010) environment. The implementation deploys HAMBase (van Schijndel 2007) and Radiance (Radiance 2010) as incorporated simulation tools.

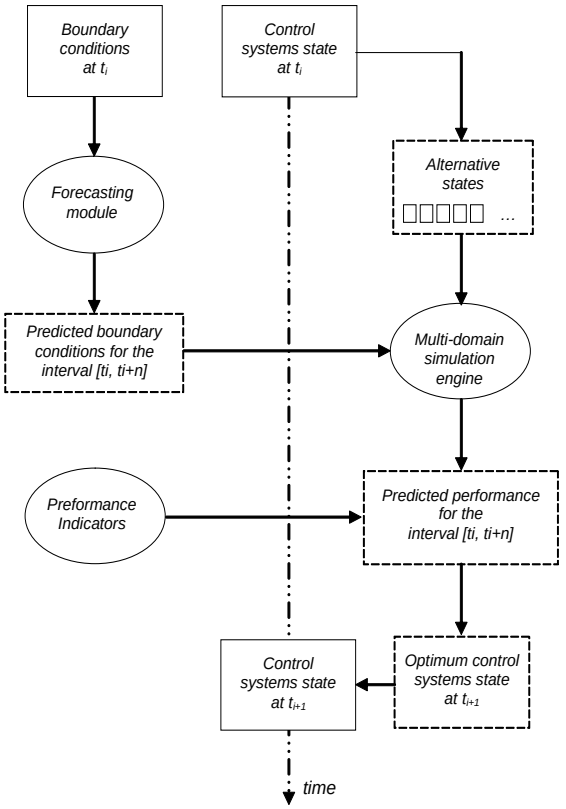


Figure 8. Illustration of the predictive simulation assisted control strategy

These simulations results are the basis for the evaluation process to generate optimum control decisions according to defined performance indicators. This predictive control approach operates in difference to the commonly used reactive feedback based standard control methods used in building systems control. Instead of using differences of the set values and actual values, this approach optimizes the system operation in a holistic way.

Alternative States

To feed the predictive control method with alternative operation states, the relevant device control schedules have to be produced. The generative process of schedules uses genetic algorithms. A number of default operation schedules are used together with randomized schedules as the initial setup. Needed state definitions and device attributes are stored in a predefined data structure (Figure 9) to generate the schedule automatically.

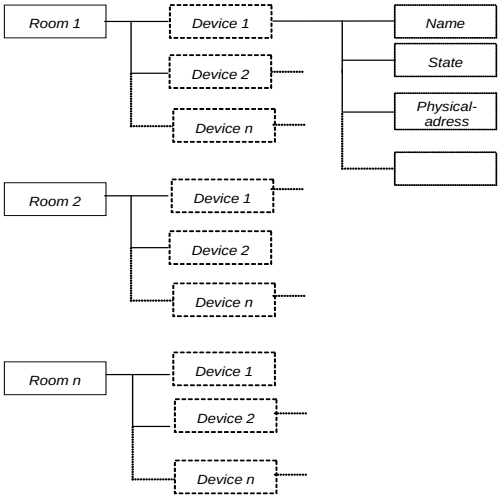


Figure 9. Schema for device attribute definition data structure

Based on the first generation simulation the best-ranked schedules were selected to generate new child schedules in a random multipoint crossover reproduction process (Figure 10). For this purpose, the high-ranked schedules are crossed with themselves as well as with additional randomly selected schedules dealing as parent elements.

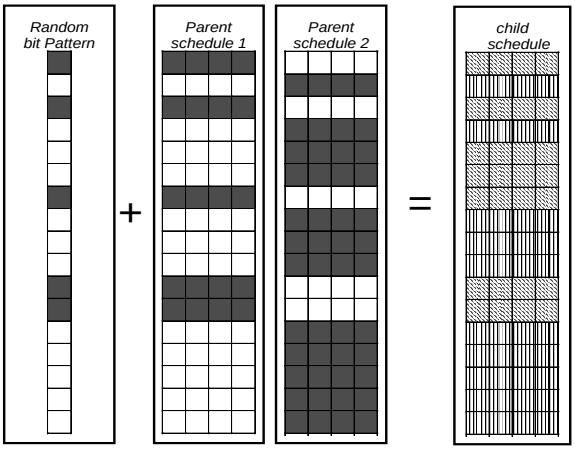


Figure 10. Illustration of the genetic multipoint crossover reproduction

The ranking is done by a number of performance indicators (discussed below) to estimate the fitness of each alternative state. Figure 11 illustrates this genetic approach.

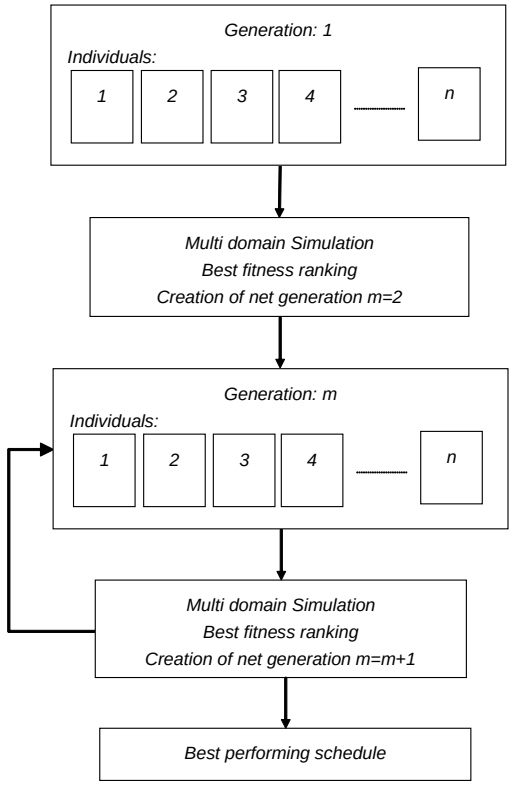


Figure 11. Illustration of the genetic generation of the desired operation schedules

Performance Indicators

A holistic evaluation of alternative system operation scenarios with related control system states is the core component of this control method. A set of building performance indicators weighted with associated weighting factors were used to evaluate the multi-domain simulation results and rank the alternative control state scenarios. The performance indicator i (Equation 1) is the weighted sum of all indicators i_x. The value of each indicator and the sum of the weighting factors w_x is in the range of 0 to 1. Hence i must be in the same range. The ranking of the alternatives is done by maximum to minimum sorting.

$$i = \sum i_x \cdot w_x \qquad (1)$$

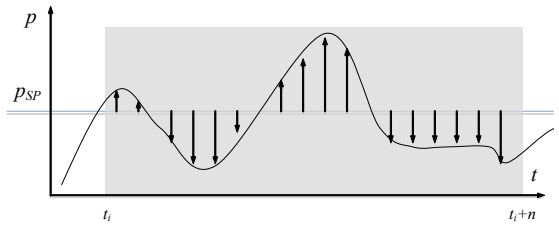
$$i, i_x, w_x \ni [0,1] \quad \text{and} \quad \sum_x w_x = 1$$

The calculation of each indicator is based on the simulated predictive trend of the related system parameter (e.g. air temperature of a room). For each specific parameter, the sum of deviations d_{period} is calculated for the future n time steps shown in Equation (2).

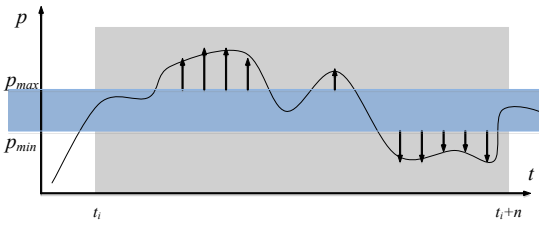
$$d_{period} = \sum_{k=t_i}^{t_i+n} d(k) \qquad (2)$$

The calculation of each deviation depends on a fixed set point or an acceptable parameter range as shown in Figure 12. The general indicator i_x could be derived either linearly (Figure 13), or exponentially (Figure 14).

The principle calculation procedure for power respectively energy indicators is presented in Figure 15 and expressed for HVAC and lighting power use.

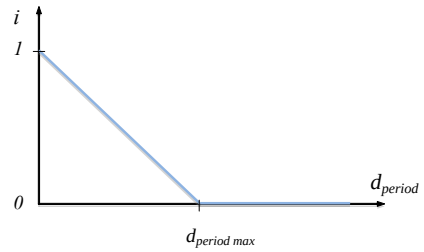


$$d(t) = \left| p(t) - p_{SP}(t) \right|$$



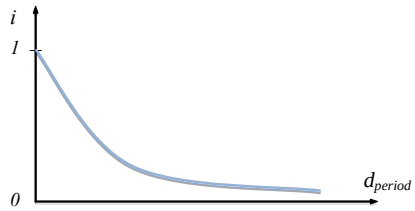
$$d(t) = \begin{cases} p_{min} - p(t) & if \quad p(t) < p_{min} \\ 0 & if \quad p_{min} \le p(t) \le p_{max} \\ p(t) - p_{max} & if \quad p(t) > p_{max} \end{cases}$$

Figure 12. Deviation d calculation for a general system parameter p.



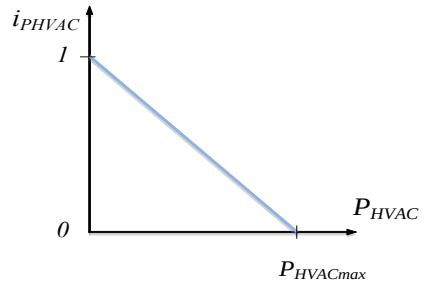
$$i_x = \begin{cases} 1 - \dfrac{d_{period}}{d_{period\ max}} & if \quad d_{period} < d_{period\ max} \\ 0 & if \quad d_{period} \ge d_{period\ max} \end{cases}$$

Figure 13. General linear performance indicator i_x calculation.



$$i_x = 1 - e^{-c.d_{period}}$$

Figure 14. General exponential performance indicator i_x calculation.



$$i_{PHVAC} = \frac{1}{n}\sum_{t=t_i}^{t_i+n} 1 - \frac{P_{HVAC}(t)}{P_{HVAC\ max}}$$

$$i_{PL} = \frac{1}{n}\sum_{t=t_i}^{t_i+n} 1 - \frac{P_{Lighting}(t)}{P_{Lighting\ max}}$$

Figure 15. Performance indicator for power or energy related parameters, as expressed for HVAC or Lighting related power use P_{HVAC} and $P_{Lighting}$.

RESULTS

Data is being collected in both test rooms toward an objective documentation of the indoor-environmental conditions. To obtain an initial impression regarding the impact of window ventilation on indoor temperature, measurements of the external temperature θ_e [°C], the test room's air temperature θ_i [°C], and the window opening pos_w [%] are shown in Figure 16 for a typical summer week. Thereby, the influence of two instances of (manual) window operation can be seen. Both rooms have a very strong overheating tendency caused by the limited thermal mass and the oversized windows. The usual summer day temperature is in the range from 20 to 30°C with peaks up to 35°C.

Simulated natural ventilation

Parallel to the monitoring phase, thermal simulations were done to estimate the night cooling effect and virtually test the new control approach. For this purpose, measurements of air change rates were the starting point for different natural ventilation simulations in EDSL Tas (EDSL 2008). Figure 17 shows the external air temperature θ_e and the simulated indoor air temperatures θ_i for a typical summer week. The simulation was done for an air change of 0.4, 1.4 and 10 h^{-1} over 24 hours a day. A ventilation regime with an air change rate of 0.4 h^{-1} over the day (8am to 7pm) and 10 h^{-1} during the night hours was simulated as well. These simulations indicated the overheating tendency of the rooms, but also showed the potential of natural ventilation.

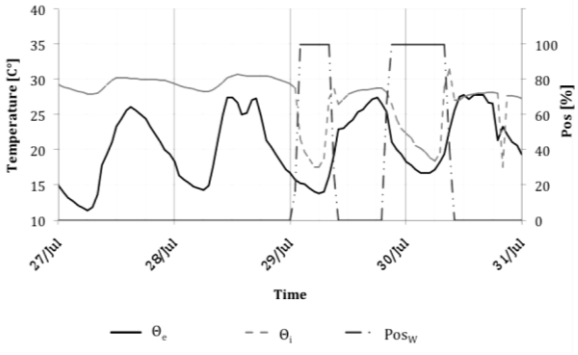


Figure 16. Measurements in first floor test room for period 21. – 31. July

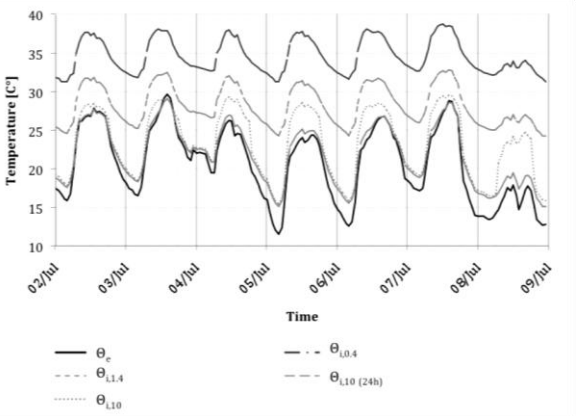
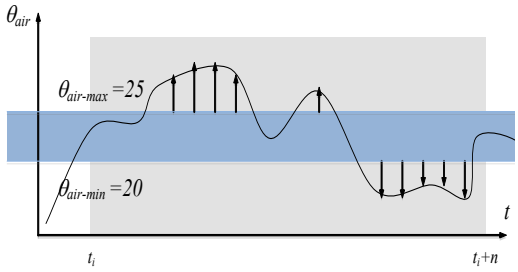


Figure 17. Simulated indoor air temperatures as a function of air change rates

Control approach Implementation

To demonstrate the advantages of the predictive control, a first implementation was done in a virtual setup. Based on the HAMBase simulation package (van Schijndel 2007) for MATLAB a thermal model of the two test rooms was created. Adaptations to HAMbase were carried out for the control of shading and the possibility to run single hour step simulations with stored data. The development and integration of the complete control system was also done in MATLAB. Components for the collection of required data (weather forecast, internal/external sensor data) and their storage into a sqlite database were programmed in C. These could be run independent of the control program as a service.

At this stage only the room air temperature was used as a performance indicator. The comfort zone for the room temperature was assumed to be the range between 20 and 25 °C (Figure 18).



$$d_\theta(t)=\begin{cases}\theta_{air-min}-\theta_{air}(t) & if \quad \theta_{air}(t)<\theta_{air-min}\\ 0 & if \quad \theta_{air-min}\le\theta_{air}(t)\le\theta_{air-max}\\ \theta_{air}(t)-\theta_{air-max} & if \quad \theta_{air}(t)>\theta_{max}\end{cases}$$

Figure 18. Deviation d calculation for the room air temperature

Result of a test using measured external climatic data and the HAMbase model is presented in Figure 19, Figure 20, and 22. Each plot shows the historical data including the real external air temperatures and the simulated indoor air temperatures on the left half of the plots. Simulated temperatures for all scenarios (generated via the aforementioned genetic approach) are presented in grey color on the right half side together with the status of windows (green) and shades (blue) for the best performing scenario (black). Concerning the status scale, 1 denotes fully open windows and fully closed shades.

These Figures represent 3 consequent days. They illustrate the large difference between weather forecast and actually measured temperatures. However, the performance of the system (i.e. identification of the best performing scenario) does not appear to be adversely affected by such weather forecast errors.

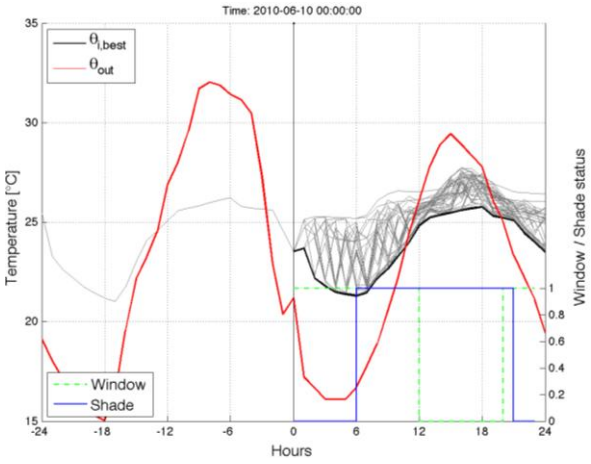


Figure 19. Temperature of the test room ($\theta_{i,sim}$), 2010-6-10 00:00

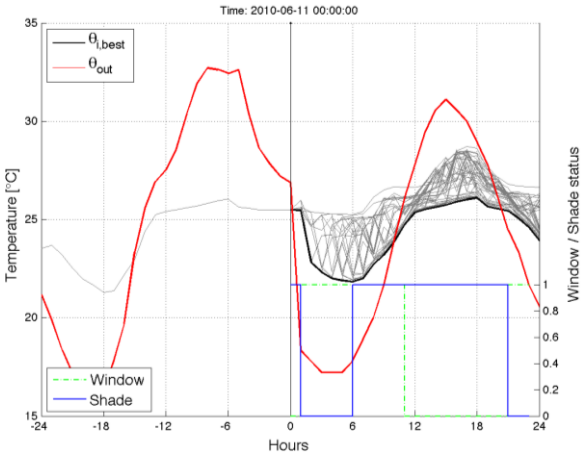


Figure 20. Temperature of the test room ($\theta_{i,sim}$), 2010-6-11 00:00

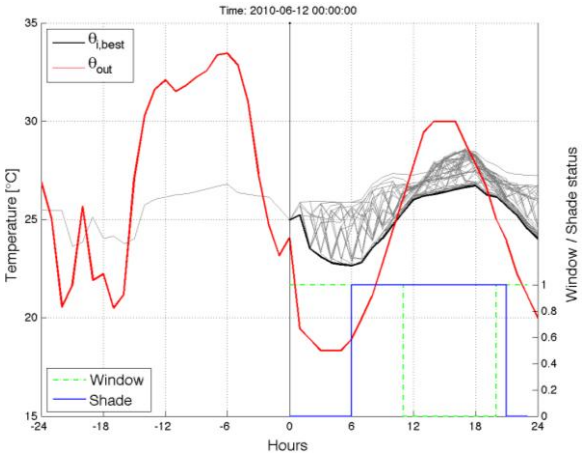


Figure 21. Temperature of the test room ($\theta_{i,sim}$), 2010-6-12 00:00

DISCUSSION

The scope and the initial results of a prototypical implementation of a simulation-assisted predictive control approach for passive cooling were presented in a recently constructed office building in Austria. Thereby, the potential of the method was primarily explored toward harnessing natural ventilation (via window elements equipped with software-controlled actuators) and solar control (via automated shading devices). The results thus far point to the potential of the proposed control method, which involves the dynamic and parametric use of numeric simulation of genetically generated alternative control options to proactively assess, compare, and evaluate control these options toward identification of the control actions that yield appropriate indoor-environmental conditions while minimizing energy use. Future efforts will focus on the long-term test and monitoring phases in occupied settings.

ACKNOWLEDGEMENT

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