Model-assisted control through co-simulation for intelligent Building Energy Management Systems design

G.I. Giannakis, K.I. Katsigarakis & G.D. Kontes
Department of Production Engineering and Management, Technical University of Crete, Greece

D.V. Rovas
Group of Energy Systems, Fraunhofer Institute for Building Physics, Germany

ABSTRACT: Effective and parsimonious use of energy resources and climate control systems is a prerequisite for reduction of energy intensity of the building sector; intelligent Building Energy Management Systems (BEMS) can be key ingredients towards achieving this goal. While most BEMS are implemented as a collection of static rules, research effort has been given towards automatic BEMS design. In the present work, a model-based methodology for automatically designing BEMS, developed within PEBBLE FP7 project, is presented. A co-simulation setup is implemented, where a detailed thermal simulation model of the building is used as a surrogate of the real building and, at pre-defined time-intervals, a model-assisted control design optimization is used to produce update control strategies, applied to the building. Moving towards real-world implementation, a middleware integration component is used to facilitate two-way communication between the building (sensing and actuation) layer and the algorithmic layer. Experimental results on a test site located in Greece, indicate the effectiveness of the proposed methodology towards automatically generating good, in terms of energy performance, control strategies.

1 INTRODUCTION

In the design and operation of positive-energy buildings a pragmatic target is maximization of the actual net energy produced (NEP) by intelligently shaping demand to perform generation-consumption matching. To achieve this, informed decisions in (almost) real-time are required to operate building subsystems and to account for unpredictable user-behavior, occupancy scheduling and occupants' activity and changing weather conditions. These decisions have direct consequences to occupant thermal comfort, energy efficiency and, ultimately, to the NEP. The complex interplay between the many parameters precludes empiricism or rule-based decisions and necessitates the development of generic decision tools.

As maximization of the NEP for Positive-Energy Buildings is attained thru Better ControL dEcisions (PEBBLE), a control and optimization ICT methodology that combines model-based predictive control and cognitive-based adaptive optimization is proposed for automatic Building Energy Management Systems (BEMS) design. There are three essential ingredients to the PEBBLE system: first, thermal simulation models, that are accurate representations of the building and its subsystems; second, sensors, actuators, and user interfaces to facilitate communication between the physical and simulation layers; and third, generic control and optimization tools that use the sensor inputs and the thermal models to take intelligent decisions. Building occupants have a dual sensor-actuator role in the PEBBLE framework: through user-interfaces humans act as sensors communicating their thermal comfort preferences to the PEBBLE system, and in return the PEBBLE system returns information with the goal of enhancing energy-awareness of the users. The generality of the proposed methodology affords a universality that transcends regional, behavioral, environmental or other variations.

Within the PEBBLE Project, a detailed zonal-type thermal simulation model developed during the design phase of the building, along with a co-simulated control design process utilizing a stochastic optimization algorithm and weather and occupancy forecasts, is used to automatically generate control strategies, that use energy parsimoniously while preserving thermal comfort at acceptable levels. The methodology presented here is demonstrated by application of the PEBBLE system in a real building, located in Greece, in the context of a heating experiment in which the model-based control strategy is shown to yield good operational performance, effectively balancing the requirements of reducing energy consumption while maintaining acceptable thermal comfort levels for the building occupants.

1.1 *The experimental set-up*

The study building is the Maintenance support building of the Technical University of Crete located in Chania, Greece (Dröscher et al 2010). In addition to thermal comfort problems for the building users, the energy consumption of the specific building is quite high, at 130kWh/m^{2}a, based on energy audits and simulation results. The TUC building is unspectacular in most ways and in that sense typical of many existing office buildings in Greece and elsewhere. It has a glass roof (that can be used for buoyancy-driven natural ventilation) and manually-controlled shading devices and windows in all 10 offices of the building. Figure 1 shows the front entrance of the building.

Figure 1. The Maintenance support building of the Technical University of Crete.

1.2 *The simulation model*

As stated earlier, in the core of the PEBBLE system lays a simulated model of the building at hand, used to assimilate and predict the actual building conditions. Even though successful applications using quasi-linear models for the building exist (Oldewurtel et al. 2012), within PEBBLE detailed thermal simulation models have been utilized. Thus, following the PEBBLE approach, a simulation model of the TUC building has been developed using EnergyPlus (Crawley et al. 2005).

To start, the effective simulation of the building requires accurate description of local climatic data. As part of the effort of having real-time data for simulation purposes, a weather station was installed on the building site allowing for the continuous monitoring (and recording) of the pertinent meteorological parameters, along with an automated procedure for the generation of the related weather files (to be used for simulation purposes in the validation phase of the project).

A detailed representation of the building geometry was created according to the floor plans using the DesignBuilder drafting environment which is a graphical editor for the generation of the EnergyPlus input files. To account for shading from nearby buildings, along with the building geometry, the shapes of neighboring buildings were introduced during the design phase.

To correctly account for internal gains due to occupant presence, activity data were collected for the building and imported to the EnergyPlus simulation engine, including occupant density (people/m^2) on each zone, occupancy timetables (including holiday schedules) and metabolic rates for office activities. Moreover, actual energy-use equipment, such as computer and electrical equipment gains, were introduced for each zone of the building. Utilizing building construction information, templates were created for each of the walls (internal partitions, external walls, roof etc.) detailing thermal characteristics.

Regarding the HVAC system of the building, heating is achieved through a central system using an oil boiler and hot water radiators in each room. Towards modeling the HVAC system in EnergyPlus, a dual setpoint thermostat was introduced for each zone, which is heated with separately heating setpoint temperatures. Data regarding the heating and cooling function of each type of split unit in each zone, such as availability schedule, air flow rates, EER, COP and capacity, were introduced.

The central heating system was modeled with details referring to the boiler (fuel type, thermal efficiency, water temperature), the radiators located in each zone (average water temperature, water mass flow rate, capacity, surfaces and fractions of radiant energy to surfaces) and the connection of the boiler with the radiators in each zone (branches, splitter, mixer). Upon completion of the design phase, the model was calibrated and validated using actual sensor data from the building (Pichler et al. 2011a) and was made available for use by the PEBBLE system.

1.3 *The Control Problem*

Since a detailed thermal model of the building is utilized for the BEMS design process, classical control design techniques, targeted to linear or quasi-linear state-space models (Ma et al. 2010, Oldewurtel et al. 2010) do not apply. Thus, the available model is treated as a black-box model and a stochastic optimization algorithm facilitating multiple controller evaluations on the model is used to produce proper control strategies.

Since model inaccuracies are unavoidable and weather predictions cannot be reliable for more than a few days, a model-assisted control technique is developed, in accordance to Model Predictive Control (MPC) approaches (see Goodwin et al. 2005), already used successfully in building domain (Oldewurtel et al. 2012).

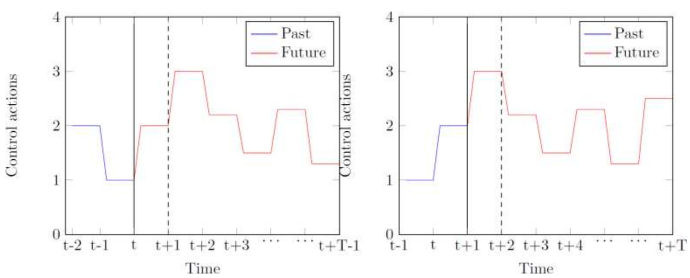

Figure 2. Model Predictive Control at time-step t (left) and at time-step t+1 (right).

In this setting, a controller is designed for the building for a period of time (prediction horizon) T, which is the limited time-window where accurate weather forecasts are available. Then, the controller is applied for a smaller period of time T' (the control horizon) and a new controller is designed for the prediction horizon. A schematic representation of the process is shown in Figure 2 (Goodwin et al. 2005):

- At time t (current time), the control problem is solved for the prediction horizon $[t,\ t+T-1]$, using the model of the building and the available predictions.
- The resulting controller is applied for the control horizon $[t,\ t+1]$ and the process restarts.

The defined optimization problem cannot be solved analytically, since it is non-linear, non-convex, an analytical state-space model is not available (as we are using the EnergyPlus simulator) and the optimal solution is difficult to be determined. Moreover, each controller evaluation on the model is expensive, due to the detailed nature of the building thermal simulation.

To overcome these obstacles, a fast and efficient stochastic optimization algorithm is used, called Cognitive-based Adaptive Optimization Algorithm with Constraints (CAO-C), successfully applied in energy-efficiency tasks in buildings (Pichler et al. 2011b, Kontes et al. 2012a, Kontes et al. 2012b).

In CAO-C, the optimization problem is defined as the minimization of a performance index (e.g. the total energy consumption), while satisfying a set of constraints, i.e. keeping acceptable thermal comfort levels for the occupants. Note that here, a critical factor in determining efficient control strategies for heating and cooling is end-user (building occupant) thermal comfort which, according to EN15251 standard (CEN 2007) should not be violated except, maybe, for small intervals during the building operation. In that sense, thermal comfort constraints should be satisfied by all acceptable control strategies. Dry-bulb temperature tracking has been used as a comfort estimation criterion (Oldewurtel et al. 2010); still, neglecting humidity and radiant temperatures can lead to insufficient estimation of the actual thermal comfort, especially for buildings with high thermal mass. The Fanger index (ASHRAE 2004; ISO 2005) or adaptive thermal comfort models (Azer & Hsu 1977) can yield a realistic estimate of thermal comfort, but their computation requires hard-to-measure parameters. Nevertheless, for BEMS design these can be comprehensibly approximated utilizing thermal simulation. In the present work, Fanger PPD index has been selected as a measure for comfort and is used in the control-design process.

In the CAO-C algorithm the following steps are implemented :

- First, an estimator for the cost function is constructed along with one approximator for each of the comfort constraints.
- Subsequently, the best controller so far in the optimization process is selected, and a set of candidate controllers in the area around the best one are selected.
- Each candidate controller is evaluated on the cost function and constraint estimators.
- After all candidate controllers are evaluated, the controller that satisfies all comfort constraints (as predicted by the comfort estimators) and has the lowest (for minimization) or the highest (for maximization) score (as predicted by the approximation of the performance index) is selected to be tested on the simulator for the next iteration of the algorithm. If all candidate controllers do not satisfy all the constraints, the controller which less violates the constraints is selected for the next iteration.

Note here, that estimating the performance of a controller on the approximator is computationally much cheaper than evaluating on the simulator. The whole process is repeated until the algorithm converges to a final controller. For more information on the stochastic optimization algorithm, please refer to (Kontes et al. 2012a).

1.4 *Co-simulation*

With the thermal model of the building and the stochastic optimization algorithm available, a module allowing information exchange between the two is necessary. This is achieved through the co-simulation setup, which: a) incorporates into the simulation historical weather and in-building sensor data; b) injects weather and occupancy forecasts in the simulation model; and c) facilitates simulation scenarios using dynamical actuating schedules, thus allowing the evaluation of the candidate controllers. Note here, that the utilization of historical sensor and weather data is crucial for the accuracy of the thermal model, since allows for effectively estimating the initial thermal state of the building during the initiation of the control design process.

In our case, the dynamic connection between EnergyPlus, where the model of the building has been developed, and Matlab, where the control logic has been implemented has to be effectively utilized. Such a connection can be achieved using EnergyPlus with External Interfaces and especially with the Building Controls Virtual Test Bed (BCVTB) (Wetter & Haves 2008). The BCVTB is a software environment, developed by Lawrence Berkeley National Laboratory which enables the coupling of different software codes for distributed simulation, by allowing simulation of the building envelope and HVAC system in EnergyPlus and implementation of the control logic in Matlab (or other general purpose programming languages), facilitating dynamic data exchange between the two software at each time step of the simulation.

2 BUILDING MANAGEMENT SYSTEM

The simulation components described in the previous section produce, at fixed time intervals, controllers to be applied to the building. Since the selected controller may rely on real-time sensor information (e.g. a PID controller) and the accuracy of the model depends on the availability of historical sensor data, utilization of the BEMS system of the building is essential for successful application of the PEBBLE system.

2.1 *Data access*

The plethora of sensing and actuating components hinders the intercommunication with PEBBLE System, since a variety of different field-level communication protocols have to be treated transparently and effectively. A schematic of the connection, as it applied for the experimental site is shown in Figure 3. Here, wired and wireless sensors are connected to PLCs and communicate values using different protocols: wireless EnOcean-based sensors communicate to the PLC via EnOcean telegrams, while at the same time, in a different PLC, CSEM sensors connect to the PLC using the serial port to exchange CSEM telegrams and KNX components communicate directly to the same PLC, sending EIB telegrams.

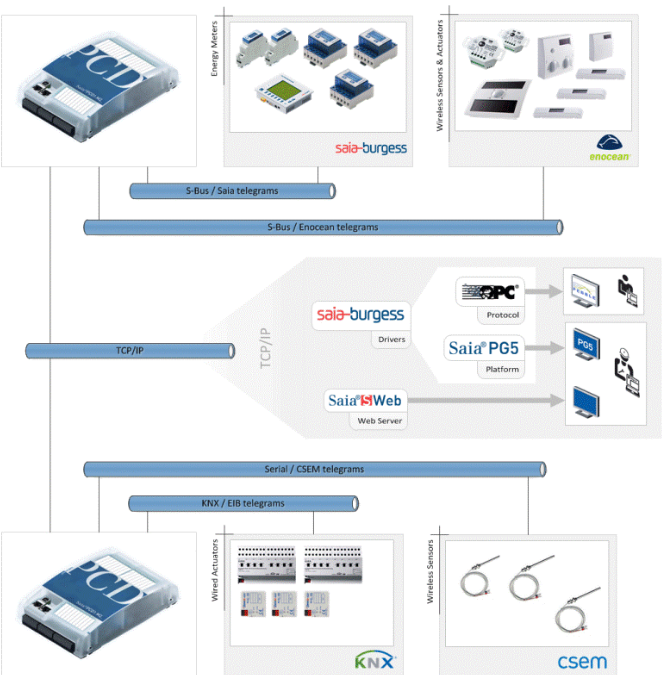

Figure 3. Sensor Communication.

Subsequently, the data from the PLCs must be redirected to the outside layer, so that data-loggers can store data in databases or to be reported to users. Field-device protocols are read and interpreted at the PLC-level. Appropriate FUPLA boxes, e.g. for the CSEM WiseMac protocol, have been developed. All this data is then made available from the PLC via a web-based CGI interface. Alternatively the OPC DA access method can also be employed.

2.2 *Monitoring and data-logging*

One of the design considerations was to provide high availability of the data logging system to ensure minimum loss of data points for the evaluation. To satisfy this requirement, the monitoring architecture comprises two-data logging virtual machines, each of which is connected to the information network and receives the data values via the OPC server. Restarting one of the two data-logging machines (for maintenance or repair purposes) automatically switches the data logging to the other one. High availability is applied at two levels: at the physical machine layer and at the application level.

At the physical machine layer, two VM servers are concurrently running and the physical machine is automatically (transparently) transported to the other machine in case either VM server experiences a physical or component failure.

At the application level, the databases running on the two data logging VMs are constantly kept up to date using database mirroring technologies. In addition, log shipping is used to update a third database running on another machine (to off-load) some of the transactional load, while keeping an active backup. Finally, a backup solution takes a snapshot of the database every 15 minutes so that a copy of the recorded data is kept off the building site.

The simulation workstations connect to the secondary database, and can query for information needed by the PEBBLE system for simulation, evaluation or, most often, control-design purposes. To ensure data security and protection, high-level encryption is used for the transmission of the data utilizing a Kerberos-based system.

2.3 *Connection to external data sources*

PEBBLE System requires connection to external data sources, as well as to external tools to effectively complete each task required. In this context, PEBBLE System has to be connected to the following external modules:

- to a weather service, in order to acquire weather predictions,
- to a dedicated weather station to collect and store real-time weather data,
- to the optimization module, for constant update of the controllers applied to the building,
- to properly configured GUIs to be able to provide data and functionality on demand to the users.

Figure 4 shows the interplay between building-side components and external sources. In order to ensure transparency, a set of services “live” on the building side, while a set of services are deployed in

PEBBLE Cloud. Following this approach, in TUC building a database system is running and storing any available sensor measurements or actuating commands, making them available for future use. At the same time, within PEBBLE Cloud, a dedicated service gathers and stores weather predictions in predefined time intervals, a control design process constantly generates new, improved control strategies that are up-to-date with the latest weather predictions and building data, and a set of GUIs are available in order to monitor building behavior and perform administrative tasks. The data-access protocols described above ensure constant and robust data access from all available sources, enabling transparent data fusion.

Figure 4. Connection to external data sources.

2.4 *Users and user engagement*

Users within PEBBLE act both as sensors and actuators, assisting the control decisions of the system. Within this context, users are allowed limited control on the HVAC system, by communicating their preferences. But in order for the users to make energy efficient decisions, information has to be provided on the impacts of their decisions, using e.g. energy consumption charts. Moreover, in order to promote user-acceptance on the system, a detailed set of information concerning the conditions in their room has to be provided.

In order to include the above options in PEBBLE System, a set of user GUIs has been developed, supporting a multitude of access methods and a plethora of available information provided to the users. Of course, since not all users should have access in all the sensors and components of the building, user groups have been created, allowing user occupants access only to their room and corridor data, and a group of administrators with access to all the components. In fact, the design of PEBBLE System allows for effortless definition of new user groups, with custom access to various sensors and actuators. Within this concept, a set of GUIs has been developed, targeted to different monitoring devices, including a UI for access through mobile devices, a UI supporting access through micro-browsers and a UI allowing connection through web-browsers.

3 EXPERIMENT

The experimental methodology is shown in Figure 5. Here, the BEMS design consists of three components:

- The warming-up phase: here, historical sensor and weather data are collected by accessing the database, and using the co-simulation module are injected to the simulation model, to properly warm-up the simulation model so that it matches correctly with the actual thermal state of the building.
- The control design optimization phase: here, weather and occupancy forecasts are provided to the simulation model, thus enabling accurate evaluation of the candidate controllers produced by CAO-C algorithm. The outcome of this phase is a new controller to be applied to the real building.
- The control application phase: here, the most recent controller provided by the control design module is used to design control strategies for the building, using real-time sensor and weather data.

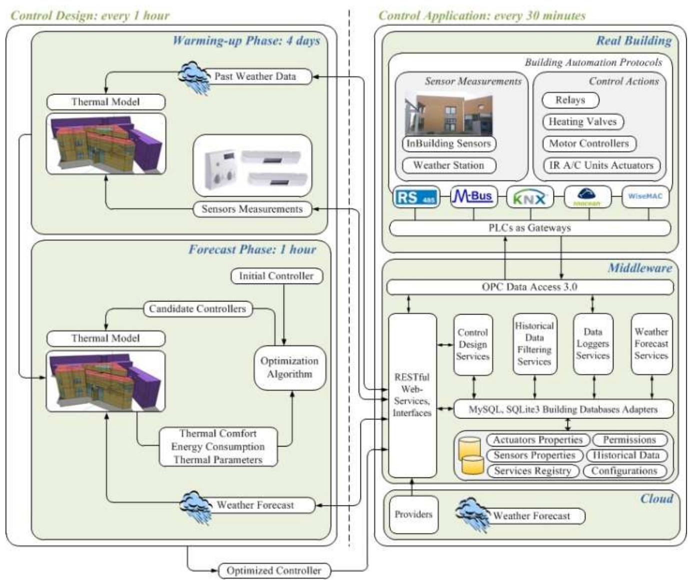

Figure 5. The experimental methodology.

An initial experiment, designed according to the aforementioned structure was conducted for two winter days (26/02/2013 – 27/02/2013). In this experiment, the valves of two branches serving two radiators in offices O4 and O5 (see Figure 6 and Figure 7) are controlled. Since office O4 contains another radiator served by a different line, which is always open, the goals of the experiment are:

- PEBBLE System should identify that O4 is being served by two different lines and try to save energy if only one is sufficient for heating the office the specific days. In addition it should produce an energy-prone control strategy for the line serving Office O5.
- PEBBLE system should produce control decisions that keep acceptable comfort levels in both offices.

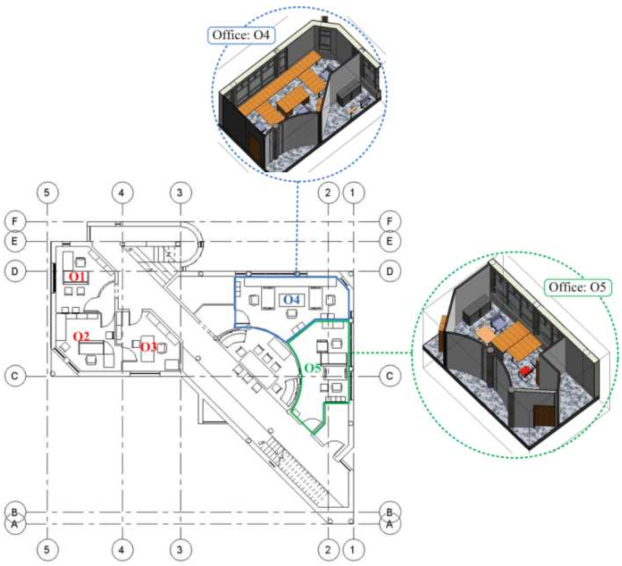

Figure 6. Offices O4 and O5, where the experiment was conducted.

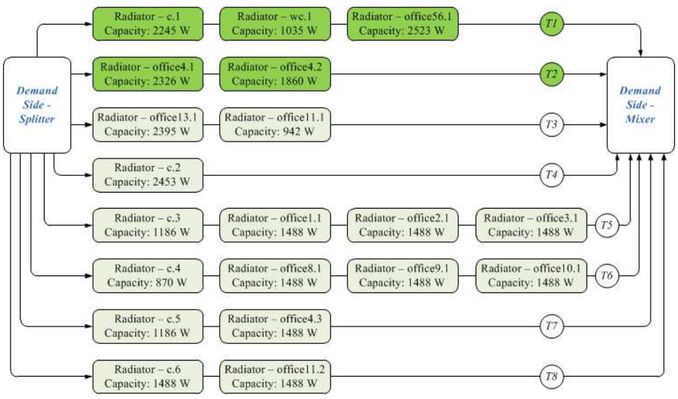

Figure 7. Central heating system branches and corresponding flow valves.

In all the experiments conducted in the real building, the control problem is defined as:

$$\min \sum_{\tau=1}^{T} E_\tau$$
$$s.t. \frac{1}{T}\sum_{\tau=1}^{T}(F_\tau > F_l) < D_l \,. \qquad (1)$$

Here, T is the prediction horizon of the experiment, E_τ is the energy consumption during the interval $[\tau-1,\tau]$, F_τ is the Fanger PPD index at time τ, F_l is the Fanger PPD upper allowed limit and D_l is the percentage of time discomfort is allowed. The Fanger discomfort limit, i.e. the Fanger PPD value above which we consider discomfort is 15.3%, while the percentage of time discomfort is allowed is defined at 15%. These values were determined after examining the user cooling behavior and in cooperation with the occupants. Note here, that the allowed time of discomfort only serves as a constraint relaxation parameter assisting the optimization algorithm, while the final evaluation of PEBBLE system is performed on the violations of the Fanger PPD limit only.

The controller applied to the building consists of a set of weights θ, which transform the states X of the building into a set of control actions U in each time-step (Kontes et al. 2012a):

$$u_\tau = \theta \times x_\tau . \qquad (2)$$

For the experiment presented here, u_τ is the position (Open/Close) of each valve controlling the flow of a line at each timestep t and x_τ is a vector of states, consisting of the fields shown in Table 1 for each room. In addition, a hypothetical occupancy pattern is assumed during the control design phase, where the offices are occupied during working days from 08:00 to 16:00. This approach was selected, since even though the actual occupancy pattern is stochastic, it usually does not exceed the working hours. In addition, the controller takes into account occupancy information in the state vector, thus should be able to react to user-presence disturbances. Finally, due to lack of window opening information, the following rule was adopted for the opening of the windows, in an effort to mimic user behavior:

$$T_{zone} > T_{out} \;\; AND \;\; T_{zone} > T_{set} \qquad (3)$$

Here, T_{zone} is the room temperature, T_{out} is the outside temperature and T_{set}=24°C is a setpoint temperature properly adjusting the rule. If the rule is active, then all room windows fully open, otherwise they remain closed.

Table 1. Controller inputs.

States	Description
x_1	Outside temperature
x_2	Outside relative humidity
x_3	Solar radiation
x_4	Wind speed
x_5	Wind direction
x_6	Zone temperature
x_7	Zone relative humidity
x_8	Zone occupancy (1 for occupied, 0 else)
x_9	(Zone temperature)^2
x_{10}	(Zone relative humidity)^2

In the specific setting, a new controller for the building is designed every one hour, taking into account 4 days in the past for the warming-up process, while a new signal is sent every 30 minutes to control the valves. Subsequently, the performance of the

PEBBLE System is compared to the static rule-based controller applied to the building during normal operation (governed by the central heating campus strategy) and a comparative evaluation is performed with regards to total energy consumption and user comfort levels.

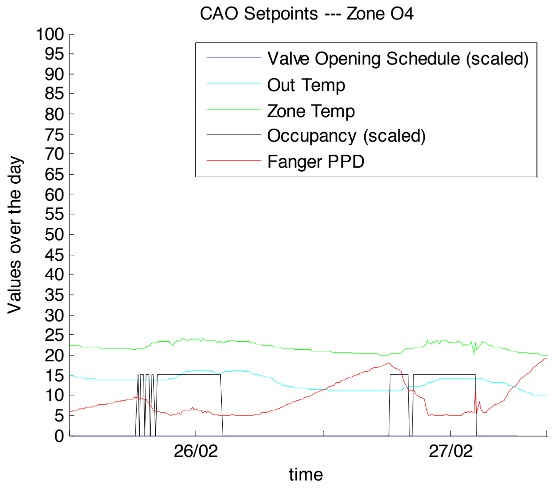

Figure 8. PEBBLE System control actions for O4.

For the rule-based controller, the central heating system serving all campus is opened every day at (about) 05:30 to pre-heat the buildings and is closed around 11:30 – 12:00, depending on the outside conditions; while the valves controlling the lines inside each building are always open.

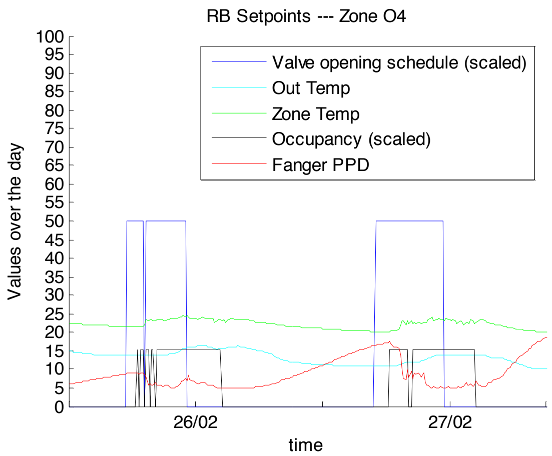

Figure 9. Rule-based controller actions for O4.

Moving to the results, a close look on the PEBBLE system behavior on office O4 reveals that the system selects to close the valve serving the controlled radiator for both days of the experiment, thus allowing the second radiator to cover the heating demands of the office. The rule-based controller on the other hand, operates both radiators serving the room (since it follows the central heating strategy of the campus), without significantly improving comfort – in fact the RB control strategy evokes 50 minutes of discomfort, during the morning of 27/02 (Figure 9), while PEBBLE system allows 1h of discomfort on the same time-period (Figure 8).

Moving to room O5, Figure 10 shows that PEBBLE system opens the valve at specific time intervals, but for fewer hours compared to the rule-based control strategy shown in Figure 11. This is due to the ability of PEBBLE system to identify that for the 26th no heating is required, using the detailed model of the building and weather forecasts. Moreover, during 27th, it operates the system in the morning to pre-heat the room and lower the Fanger PPD index in acceptable levels, but shuts it down approximately one hour sooner than the rule-based strategy, thus, again, saving energy.

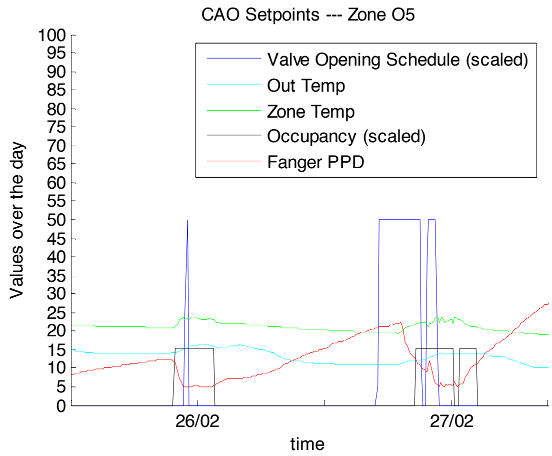

Figure 10. PEBBLE System control actions for O5.

The rule-based controller on the other hand, operates the heating system during the entire available period (determined by the central heating schedule), without achieving significant comfort improvement compared to PEBBLE system, as shown in Figure 11. In fact, both control strategies manage to maintain acceptable comfort levels to office O5 throughout the experiment, but PEBBLE system achieves no Fanger PPD violations despite opening the valve for less time.

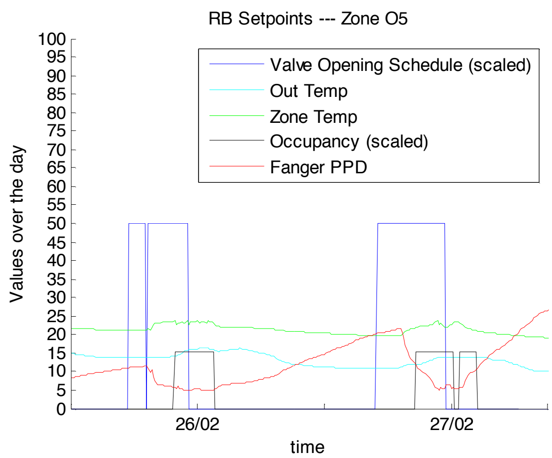

Figure 11. Rule-based controller actions for O5.

Since we are controlling only two out of the eight available central heating branches (Figure 7), the hot water consumption at each controllable line is selected as a criterion to evaluate the efficiency of PEBBLE system, instead of the building total fuel (oil) consumption. Thus, Figure 12 depicts the hot water consumption at each controllable branch, as well as the hot water consumption at offices O4, O5, for both control strategies. As shown in the Figure, 57.8% and 54.3% hot water consumption savings is achieved for offices O4 and O5, respectively, compared to the central heating strategy of the campus, for the selected days, since PEBBLE system manages to effectively utilize the information provided by the simulation model and the weather and occupancy forecasts.

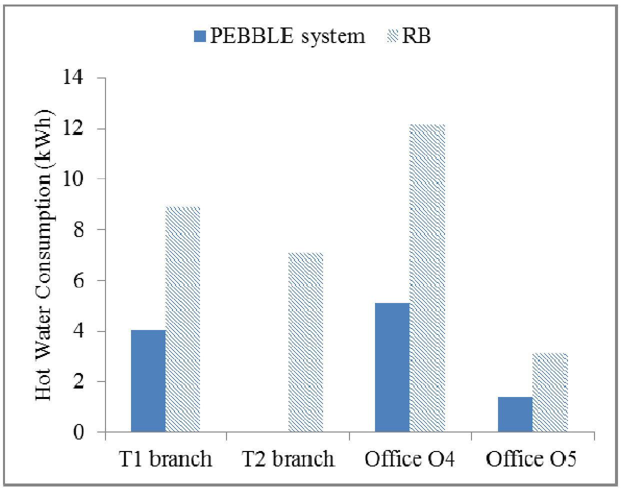

Figure 12. Experiment results – Hot water consumption.

4 CONCLUSIONS

In the present work, the overall BEMS design methodology developed within the PEBBLE project is presented. Here, a detailed thermal model of the building, along with weather and occupancy forecasts and a stochastic optimization algorithm are utilized to produce energy-efficient control strategies for a target building. Experimental investigation of the proposed approach indicates approximately 55% energy savings for a two-day heating experiment on two office rooms compared to the central heating control strategy, without compromising user comfort.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

ASHRAE 2004. *ANSI/ASHRAE Standard 55-2004: thermal environmental conditions for human occupancy*, Atlanta

Azer N & Hsu S 1977. The prediction of Thermal Sensation from Simple model of Human Physiological Regulatory Response – A Standard Predictive Index of Human Response to the Thermal Environment. *ASHRAE Transactions 83*.

CEN 2007. *Indoor environmental input parameters for design and assessment of energy performance of buildings – addressing indoor air quality, thermal environment, lighting and acoustics*, Brussels.

Crawley D.B., Hand J.W., Kummert M. and Griffith B.T. 2005. Contrasting the Capabilities of Building Energy Performance Simulation Programs.*Proceedings of Building Simulation 2005, Montreal, Quebec, Canada, IBPSA*, 231-238.

Dröscher A., Schranzhofer H., Santiago J., Constantin A., Streblow R., Muller D., Exizidou P., Giannakis G., and Rovas D. 2010. *Integrated thermal simulation models for the three buildings*. PEBBLE Deliverable 2.1.

Goodwin G.C., Seron M. and de Dona J. 2005. *Constrained control and estimation: an optimisation approach*. Springer Verlag, 2005.

International Organization for Standardization 2005. *ISO 7730:2005(E): Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria*. Geneva, Switzerland.

Kontes G.D., Giannakis G.I., Kosmatopoulos E.B. and Rovas D.V. 2012a. Adaptive-fine tuning of building energy management systems using co-simulation. *2012 IEEE International Conference on Control Applications (CCA)*. pp. 1664-1669, IEEE.

Kontes G.D., Giannakis G.I., Kosmatopoulos E.B. and Rovas D.V. 2012b. Demand-shifting using model-assisted control. *ICHMT DIGITAL LIBRARY ONLINE*, 2012.

Ma Y., Borrelli F., Hencey B., Coffey B., Bengea S. and Haves P. 2010. Model predictive control for the operation of building cooling systems. *American Control Conference (ACC)*. 2010. pp. 5106-5011.

Oldewurtel F., Parisio A., Jones C.N., Morari M., Gyalistras D., Gwerder M., Stauch V., Lehmann B. and Wirth K. 2010. Energy efficient building climate control using Stochastic Model Predictive Control and weather predictions. *Proceedings of the 2010 American Control Conference (ACC)*. 2010, pp. 5100-5105

Oldewurtel F., Parisio A., Jones C.N., Gyalistras D., Gwerder M., Stauch V., Lehmann B. and Morari M. 2012. Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings*, 45:15-27, 2012.

Pichler M.F., Dröscher A., Schranzhofer H., Contantin A., Huber M., Giannakis G.I., Exizidou N. and Rovas D.V. 2011a. *Simulation Model Improvements*. PEBBLE Deliverable 2.3, 2011.

Pichler M.F., Dröscher A., Schranzhofer H., Kontes G.D., Giannakis G.I., Kosmatopoulos E.B. and Rovas D.V. 2011b. Simulation-assisted building energy performance improvement using sensible control decisions. *Proceedings of the Third ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*, pp. 61-66, ACM

Wetter M. and Haves P. 2008. A modular building controls virtual test bed for the integration of heterogeneous systems. *Third National Conference of IBPSA-USA*, Berkeley/California.