COUPLING BUILDING SIMULATION WITH A HARDWARE REAL-TIME CONTROLLER

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ABSTRACT

The main part of energy consumption in modern buildings is used for establishing an acceptable indoor environment quality (IEQ) for work and living. Modern commercial and industrial buildings are usually equipped with building automation systems (BAS) and building energy management systems (BEMS) to achieve the required IEQ. Successful management and operational quality of these systems varies and significantly depends on initialization and "tuning" procedures within the first year of building operation. Simulation has a role to play in establishing suitable control strategies and potentially in assisting in real-time control decisions. This paper outlines the theory of simulation assisted control capability within the ESP-r transient thermal simulation program and presents a new data synchronization mechanism for communication between a virtual building model and a real-time controller. The paper also describes the first phase of experiments realized to test the prediction accuracy of the B2E algorithm in ESP-r and to calibrate the model of the experimental facility. The positive results are discussed in relation to a second experiment which connects ESP-r with an actual BEMS. This methodology can be used for estimation of the optimal initialization on a real building with a pre-tuned controller.

Keywords: synchronization, real-time, actuation, BEMS, BAS, simulation assisted control.

SIMULACE BUDOV VE SPOLUPRÁCI S REÁLNÝM SYSTÉMEM ŘÍZENÍ

Podstatná část spotřeby energie v moderních budovách je využívána k zajištění optimálního vnitřního mikroklimatu (indoor environment quality - IEQ) v pracovním i obytném prostředí. Moderní komerční a průmyslové budovy jsou obvykle vybaveny automatickým systémem řízení (building automation systems - BAS) a systémem energetické správy budovy (building energy management systems - BEMS), právě pro dosažení požadované kvality IEQ. Správa a provoz těchto systémů je značně závislá na jejich základním nastavení a následném „ladění" v průběhu první etapy provozu budovy. Příspěvek teoreticky popisuje možnost spolupráce simulace budovy a systému řízení. Využívá se zde simulačního nástroje ESP-r pro zhotovení virtuálního modelu budovy, který je pomocí metod synchronizace dat propojen s reálným systémem řízení. V článku je rovněž popsána první část z experimentů, na které je testována přesnost předpovědi chování modelu dosažené algoritmem B2E v prostředí ESP-r. Výsledky experimentu jsou diskutovány v souvislosti s druhým experimentem, který má za cíl provést propojení ESP-r s reálným systémem řízení. Tato metodika může být dále použita pro určení ideálního přednastavení systémů řízení budovy.

Klíčová slova: ESP-r, BEMS, BAS, řízení podporované simulací, synchronizace

INTRODUCTION

Clarke et. al [1] introduced code in the transient thermal software ESP-r [2] to predict an optimal start time for a building plant. The algorithm was called B2E and was devised to allow communication between a Building Energy Management System (BEMS) and the detailed building simulation software ESP-r. ESP-r has been developed mainly by the Energy Systems Research Unit (ESRU) of University of Strathclyde in Glasgow since 1980.

The joint ESRU-Honeywell experiment [1] aimed to predict the optimal start time of a plant. Data exchange between the ESRU simulator and the Honeywell controller was provided by LabVIEW. The conclusion of the 1999 paper was that the methodology was successfully proven; nevertheless major tasks were needed development to make the methodology applicable in practice:

1. Enhance calibration procedures.
2. Replace LabVIEW with a real BEMS
3. Accelerate data I/O between components
4. Improve control routines

The research presented in this paper is focused on tasks two and three: communicating with a real BEMS instead of LabVIEW and exchanging text files via TCP/IP means in a format similar to XML. The paper reports on a data exchange experiment between the simulation platform and a BEMS in almost real-time, using an actual test chamber.

In the proposed methodology, the simulator (ESP-r) and the BEMS (KOBRA) exchange two zonal data files, a synchronization file that includes operating conditions and actual measurements and a control file with actuating instructions and temperature predictions. ESP-r simulates four zones; KOBRA measures the zone environmental conditions (dry bulb temperatures in this case) and actuates the central zone plant component. The data exchange

procedure proceeds in almost real time, that is within a five minutes timestep.

Two experiments were designed to check the methodology. The first one was aimed to achieve model calibration and check the validity of predictions and was realized in December 2009. The second experiment was designed to check the methodology for the synchronization and is currently being realized. The results reported here derive from the first of the two experiments.

PREVIOUS RESEARCH

Virtual coupling/synchronization procedures have been reported by Janak [3], Yahiaoui et al [4] [5] and Jandon [6]. Janak used subhourly simulation to communicate data between ESP-r and Radiance. Yahiaoui et.al (4) have exchanged data between MATLAB and ESP-r via TCP-IP.

The papers by Yahiaoui et.al. report a methodology for run-time coupling of ESP-r with controlling software. This focuses on a direct communication mechanism between the simulation platform and the controlling software and establishes the two most promising mechanisms for data communication, involving run-time coupling.

Yahiaoui et al [5] show that run-time coupling needs to handle asynchronous events occurring when the hardware controller and the simulator have varying timesteps, as well as synchronous events occurring when the two platforms execute with an identical timestep. It is argued in the paper that the data exchange mechanism should have the ability to handle large data quantities. Following comparison of several inter-process communication mechanisms, Data Sockets and Common Object Request Broker Architecture (CORBA) are suggested as the most appropriate data exchange technologies. Finally comparing the response time of these two communication mechanisms it was concluded that CORBA appears as the most appropriate mechanism

SIMBAD is a SIMulator for Buildings And Devices developed by the CSTB [6]. SIMBAD is a data processing environment able to simulate the behaviour of a building and its technical equipment, to which a control or building can be connected by way of an interface. SIMBAD models are usually developed in MATLAB or SIMULINK and they can represent various building and HVAC installations. The initial objective with SIMBAD was to couple it with a BEMS in order to assess its typical functions, e.g. optimum start function and load shedding.

Christias et.al (7) have proposed an asynchronous communication mechanism between the BEMS and the simulator, utilizing agents to derive off-site measurements and an in-process database to store and rapidly query measurement records. The developed software provides a worldwide accessible storage space, features a graph enabled interface and more importantly allows extraction of measurements in a desired output format rather easily.

METHODOLOGY

Figure 1 shows an overview of simulation assisted control. The simulator ESP-r operates as a building conditions predictor for the KOBRA BEMS. In our methodology, simulation assisted control is achieved as follows:

- the building to be controlled is represented by a test chamber;
- the chamber measurements are synchronised to the simulation program;
- the BEMS issues a prediction query to the simulation program regarding dry bulb temperature;
- the simulation prediction is subsequently sent to the BEMS;
- the BEMS actuates a plant component at the time suggested by the simulator;
- the BEMS controls the actuating component whilst data exchange continues; the simulator can instruct the BEMS to stop component heating.

In our experiments the dry bulb temperatures of a test Chamber, shown in Figure 3, are being sensed by KOBRA BEMS. The BEMS communicates the timestamped measurements to the simulator ESP-r, which synchronizes the measurements with the simulator timestep via a temporal measurement file. The target of the simulation is to decide an optimal start time to achieve desired temperatures for the next timesteps. Once achieved, the optimal start time is sent to the BEMS, so that it initiates heating
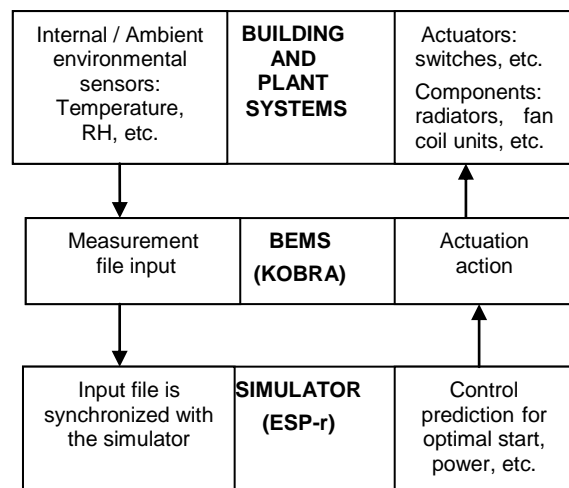

Internal / Ambient environmental sensors: Temperature, RH, etc.	**BUILDING AND PLANT SYSTEMS**	Actuators: switches, etc. Components: radiators, fan coil units, etc.
Measurement file input	**BEMS (KOBRA)**	Actuation action
Input file is synchronized with the simulator	**SIMULATOR (ESP-r)**	Control prediction for optimal start, power, etc.

Figure 1 - Simulation assisted control overview

Data communication can be either synchronous or asynchronous. In our initial experiments the communication is in asynchronous mode. In asynchronous mode a file with daily zonal measurements and a zonal short-term conditions forecast are utilised to predict conditions for the next day or after a few hours. In synchronous mode, the simulator is updated with the measurements of the previous timestep and predicts conditions for the next timestep or after a few timesteps.

The BEMS collects measurements from building controlled zones and ambient sensors. Once they are retrieved, they are sent as an input file to the simulator. The data file sent comprises an identification/synchronization key, a timestamp formatted in Unix epoch time, the ambient and internal environmental measurements and the actuation status for each zone. Similarly the output file from the simulator to the BEMS includes an exact synchronization key, an epoch formatted timestamp, the zonal temperature or IAQ predictions and the necessary control action for the BEMS, formatted as actuation percentage.

The format and an example of the two exchange files is shown in table 1. This actual example file holds only sensed dry bulb temperature measurements, and n/a (not available) is indicated for humidity and CO2 measurements. Once the file formats had been agreed, file insertion and extraction algorithms had to be developed within the simulation program. These subroutines are developed within a specific module of the program called B2E [8].

Table 1 - Data exchange formats for BEMS to ESP-r

PLATFORM	FILE FORMAT
BEMS output / Simulator input	Synchronization ID Unix Epoch timestamp, Zone ID, Measured zone temperature, Next Zone ID, Measured zone temperature, Actuation percentage status, e.g. (0;947071666;Z01,28.3 ,n/a,n/a,0;Z02,28.1,n/a,n/a,0;)
Simulator output / BEMS input	Synchronization ID, Unix Epoch timestamp, Zone ID, Predicted zone temperature, Next Zone ID, Predicted zone temperature, Required actuation percentage, Next Zone ID, etc.

The main subroutine was modified to allow input of temporal data by both the old format (via LabVIEW) and the new format (via KOBRA). Reprogramming of B2E subroutines, currently enables synchronous data exchange with a virtual and a real hardware controller, as can be seen in Figure 2. Asynchronous data exchange is also possible but a not fully automated yet.

A new subroutine was developed, B2EREAD [8]. The new subroutine reads the temporal file (which holds the measured data) from the hardware controller/datalogger of the BEMS. The timestep of the measurement is converted to the simulator timestep, in order to synchronize the timestep of the

simulator to the energy management system. Once that is achieved, the simulation initiates the prediction sequence and calculates the dry bulb temperatures for the zones controlled.

The duration of the procedure is currently less than one timestep (five minutes). Since this is not a commercial system, the duration of the procedure was considered reasonable and not much attention was given to accelerate it.

There are two operational modes in the B2E. The Optimal Start Time (OPSS) mode and the BEMS mode. The OPSS mode predicts a probable future plant startup time. It requires a climate look-ahead routine, e.g. a predictive routine that will calculate probable future boundary condition values, based on existent measurements. These future values are required by the temporal file that the simulation uses for its calculations; the temporal file holds past measurements until the point in time that coincides with the last input from the sensors/BEMS, and the generated measurements until the time target asked by the user. This time target along other standard data, such as the model's configuration are input by the user at the beginning of the procedure.
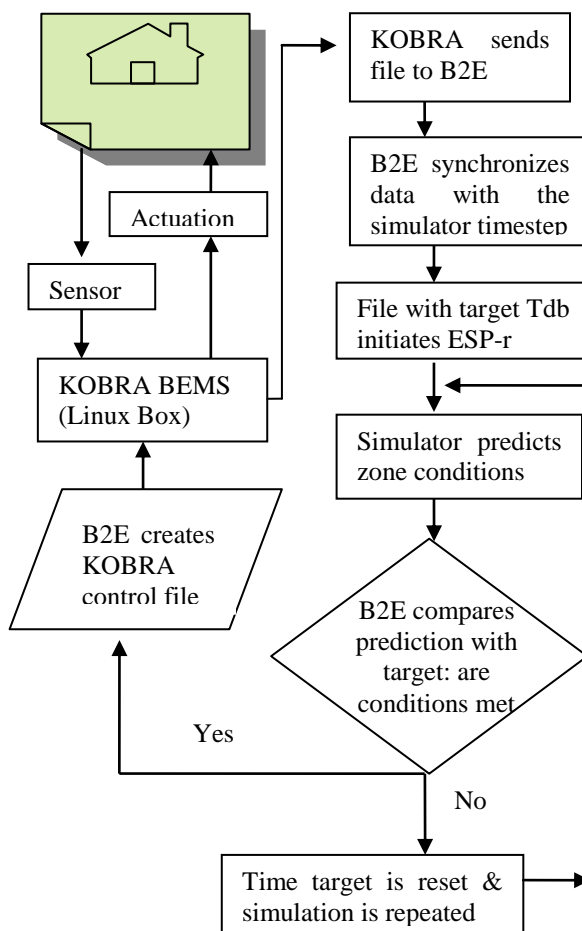

Figure 2 - ESP-r to KOBRA synchronization overview

THERMAL CHAMBER EXPERIMENTS

In order to check the methodology, two experiments have been designed. The paper reports the results from the first of the two experiments. The major aims of the first experiment were:

- Testing the precision of the predictions using the Optimal start algorithm within B2E.
- Calibration of the chamber model, shown in Figure 3.

Successful completion of these aims is important for the realization of the second experiment. The latter experiment aims to test the synchronization of the simulator with a BEMS, via data exchange in real time between ESP-r and KOBRA BEMS. ESP-r will predict the space state conditions for the next timestep, providing KOBRA with controlling decisions for various actuating components, e.g. a convection unit, as shown in Figure 2.

The simulation model shown in Figure 3, consists of four zones. The central Chamber zone which housed most sensors and the radiant heater, an adjacent Service zone with ductworks (Figure 4) and an adjacent Bounding zone which is not used. The direct measurement of temperatures on the upper zone was not possible, so a fictional zone was used. Surface sensors were attached to the ceiling of the Chamber and the values were initially superimposed to the Fiction zone of the model.
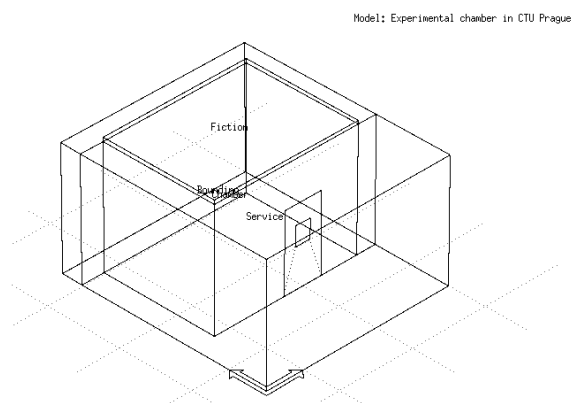

Figure 3 - Virtual model of the test Chamber

The experiments are taking place in a thermal test chamber in CTU Prague, which can be seen in Figure 4. Once the instrumentation was setup, the experimental procedure followed a pattern introduced by an innovative joint European research programme in the nineties, called PASSYS (9). According to PASSYS a specific free-floating/heating/free-cooling sequence can be used to accurately determine the thermal response of a test cell. A similar methodology has been used. Using this free floating/heating/free-cooling sequence, the model has been calibrated to match the thermal response of the actual chamber.

The test chamber is equipped with various plant components. Heating was achieved with a radiant heater with a 1kW nominal output. Thermocouples type K were placed in each one of the surfaces of the central Chamber zone. NTC type N sensors with a ±0.1°K accuracy, were placed in the Chamber, Service and Bounding zone. All sensors were logged with two ALMEMO dataloggers. Temperature measurements underneath the Chamber are made with a simple HOBO H8 datalogger, since the conditions on the basement are thermally stable Measurements were taken every five minutes. The simulation accordingly used these measurements via a temporal file which included 12 timesteps per hour.

The experimental procedure comprised of a series of typical daily heating procedure for approximately a week. The procedure consisted of a free-floating period followed by heating and a free cooling period (9).

Figure 4 - Experimental setup within the Chamber

DISCUSSION

An initial experiment was realised in December 2009 in Prague, and the results are shown in Figures 5 and 6. Figure 5 shows the simulated dry bulb temperature prediciton against the measured dry bulb temperatures for the Chamber. In the initial uncalibrated model, ESP-r overpredicts the heating, using the Alamdari-Hammond equation which assumes a perfectly mixed environment [2]; in the heavy insulated chamber this is not the case. Later measurements have indicated stratification.

Calibration was achieved by correcting the boundary conditions in the model, specifically thermal inertia and startup temperatures. Finally a small sensitivity analysis of the ratio of the convection coefficient to the radiation coefficient, enhanced calibration results.

The remaining calibration error in Figure 6, is mainly due to the convection coefficient value used for the partition between the Chamber zone and the Service zone. In order to achieve low – near ambient – temperatures in the Service zone, mechanical ventilation was used. The increased convection coefficient due to the forced ventilation was not adequately considered for that partition.
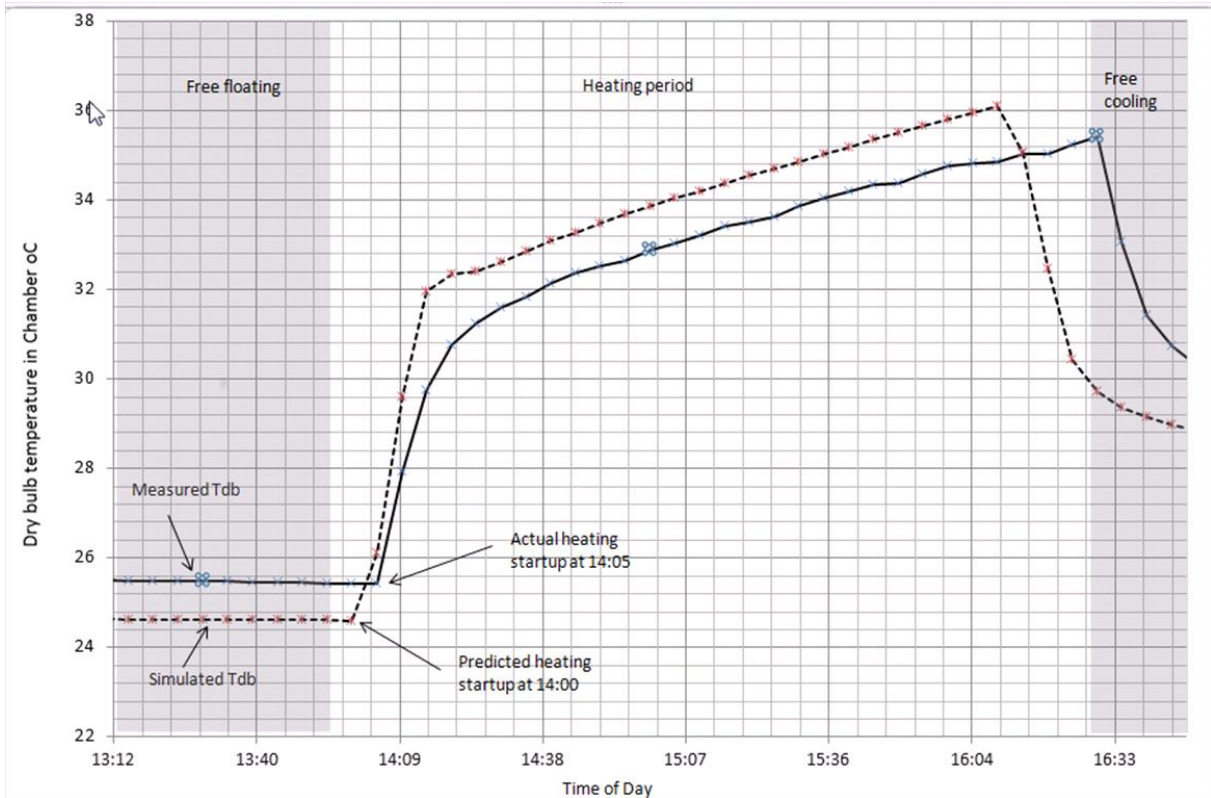
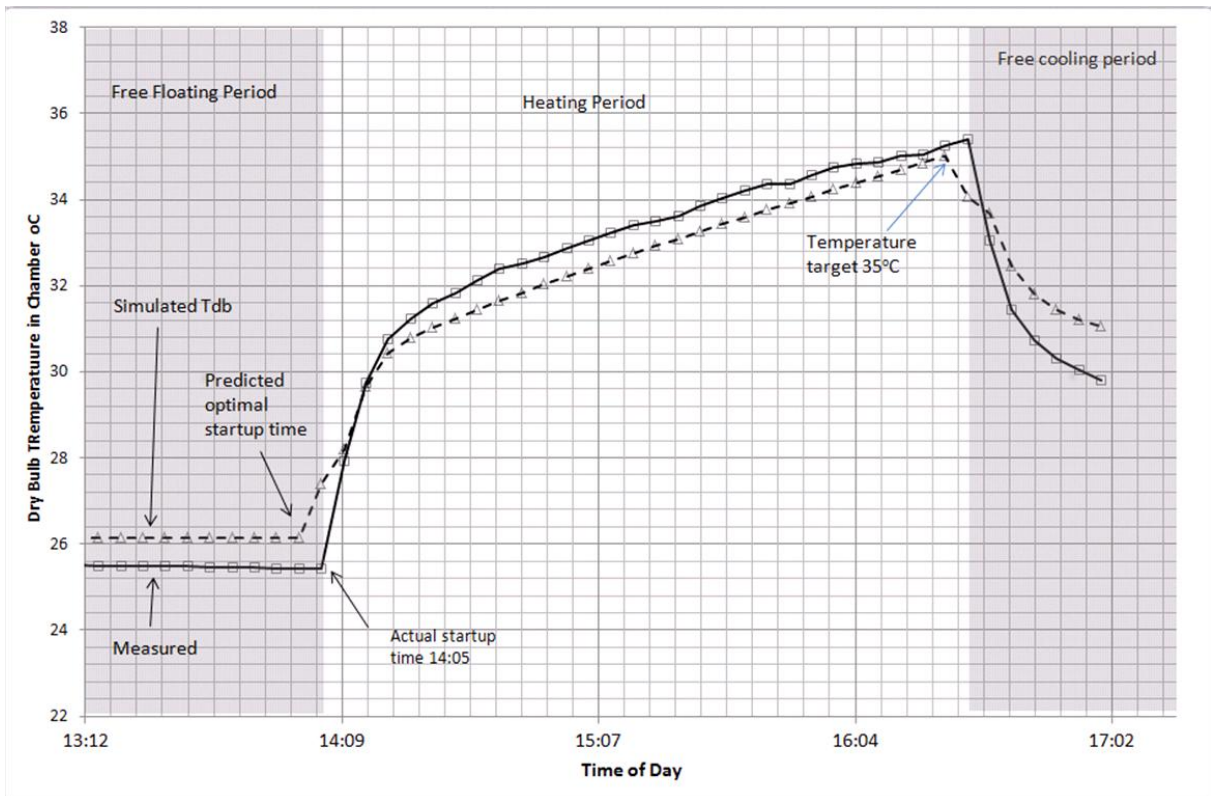*Figure 5 - Optimum start time prediction via B2E, before model calibration*

Figure 6 - Optimum start time prediction via B2E, after partial model calibration

As can be seen in Figure 6, using the measured temperatures of the adjacent zones, the B2E algorithm produced an optimal start time of 14.00, whilst the actual startup time was 14:05. The target temperature was 35°C at 16:30. The simulated temperature, is exactly 35°C at 16:25, whilst the actual temperature at 16:25 is approximately 0.2°C more than the simulated.

CONCLUSION

Results of the initial experiment were positive. The prediction algorithm within B2E was checked against a typical heating scenario and the startup times predicted were very close to the actual ones. The virtual model has been calibrated. Both initial experimental aims have been met successfully. Success of the initial experiment allows us to use the calibrated model for the second experiment to establish a synchronous data exchange between the simulator and a BEMS and test the almost in real-time predictions.

Other future tasks include:
1. Use ESP-r as an emulator for KOBRA BEMS.
2. Acceleration and semi-automation of calibration procedures and
3. Inclusion and testing of MIMO scenarios.

ACKNOWLEDGEMENTS

LITERATURE

[1] Clarke J., Cockroft J, Conner S., Hand J, Kelly N., Moore R, O'Brien T, Strachan P. Simulation assisted control in building energy management systems.. *Energy and Buildings, Vol. 34. pp933-940, 2002.*

[2] Clarke J. A. *Energy Simulation in Building Design.* 2nd ed. Oxford (UK): Butterworth-Heinemann, 2001.

[3] Janak, M. Coupling Building Energy and Lighting Simulation. *Proc. of the 5th IBPSA,* Prague, Vol. 1, 1997.

[4] Yahiaoui A, Hensen J, Soethout L. Integration of control and building performance simulation software by real-time coupling. *Proc. of the Eighth international IBPSA conference* Eindhoven, 2003.

[5] Yahiaoui A, Hensen J, Soethout L, Van Passen D. Interfacing Building Performance Simulation with Control Modelling using Internet Sockets.*: Proc. of the Ninth international IBPSA conference,* Montreal, *2005.*

[6] Jandon M, Assessing BEMS systems. *Proc. CLIMA 2000 conference.* Brussels, Belgium, 1997.

[7] Christias P, Maitos A, Voglis E. A complete software application providing automated measurements storing, monitoring and feedback for dispersed environmental sensors. *Eleventh Panhellenic Conference on Informatics, Patras, Vol. B, 2007.*

[8] Energy Systems Research Unit, Strathclyde University, Glasgow. *B2E subroutines for communication of simulator with BEMS.* URL: Http://esp-r.svn.com/src/esrub2e. [Online]

[9] Jensen SO, editor. *Validation of building energy simulation programs, part I and II. Research report PASSYS Subgroup Model Validation and Development,* CEC, Brussels, EUR 15115 EN, 1993.