A Simulation-based Control Approach in a Mechanical Ventilation System

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ABSTRACT

This paper aims to establish a simulation based control system for better building performance and low energy cost during the operational stage. This integrated system utilizes BCVTB (Building Control Virtual Test Bed) as a middleware to connect monitoring and measurement devices (e.g. sensors, meters) and a virtual model (i.e., EnergyPlus). The integrated system was established in a laboratory room with a mechanical ventilation system. A pilot test for ventilation control was conducted to see the applicability of the integrated system. This integrated system showed an energy saving potential while maintaining specified indoor air quality. As a future work, model-based control algorithms will be incorporated to the real-time simulation system for optimal control in existing buildings.

KEYWORDS

Building Energy Management System, BIM, BCVTB, Simulation based control

INTRODUCTION

Buildings consume 40% of global primary energy and contribute to over 30% of CO_2 emissions. Within building energy consumption, HVAC systems account for about 50% of the total energy used in buildings. However, a potential to save energy by utilizing energy conscious design approach and optimized building operation and control scheme can be huge. The benefits of using building simulation technologies in the design stage and operational stage have been studied in previous research (Augenbroe 1992, Pang et al. 2012). Most building energy simulation tools support the performance evaluation of a building or building systems in the design stages (e.g. whole building, HVAC systems, lighting systems, etc.). Simulation tools can also be used for continuous commission and FDD (fault detection and diagnosis). Building simulation can be used to test various control strategies in building operation for optimal performance, especially for ever-increasing complex building systems.

After introduction of building energy management system (BEMS) in 1970's, this system is a widely accepted and adopted through residential and commercial

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buildings, even in industrial complexes to achieve the possible energy and cost savings. BEMS is used to gather data related to building energy systems including HVAC system, and provide monitored data to building managers for appropriate control and operation of the building (e.g., heating, cooling and lighting). By processing and analysing the monitored data, building managers are responsible for quick understanding of the real-time state of the building to maintain occupant comfort with the lowest energy consumption. Simulation assisted building control has been studied in 2000's when robust and fast simulation tools have been developed with increased computer power. Clarke et al. (2002) studied and demonstrated predictive control using ESP-r to find optimum start time in a heating system. In his study, LabVIEW was used as a BEMS replacement.

Simulation-powered control in more realistic context has been demonstrated in a building automation test bed by Mahdavi (2009). These previous studies showed a potential for optimal control actions in building operation. Thanks to recent development of Building Control Virtual Test Bed (BCVTB), current building control and measurement devices can be linked to a building simulation program. BCVTB is an open-source software environment developed for real-time simulation and co-simulation. The BCVTB couples different simulation tools for co-simulation and data exchange with building automation system or databases for model-based operation. The simulation users can expand the capability of individual program to other programs or applications as well (Wetter 2011). This paper aims to establish and demonstrate a simulation based control system environment for maintaining acceptable indoor air quality and maximizing building energy performance in the operational stages. A case study for a ventilation system control shows comparative results among the predictive model based control and other conventional control schemes. This work is a part of a research project that develops a BEMS with a model based predictive control in multi domain optimization including heating and cooling, lighting, window operation and shading, ventilation.

FRAMEWORK AND IMPLEMENTATION

In this study, a framework for a simulation based control system is developed which incorporate an architectural BIM model to BEMS. In the operational stage, an analysis model converted from an architectural BIM model can link measured and monitored data from BEMS installed in an existing building through the proposed integrated system. Figure 1 shows a framework for a suggested simulation based control system in the operational stages.

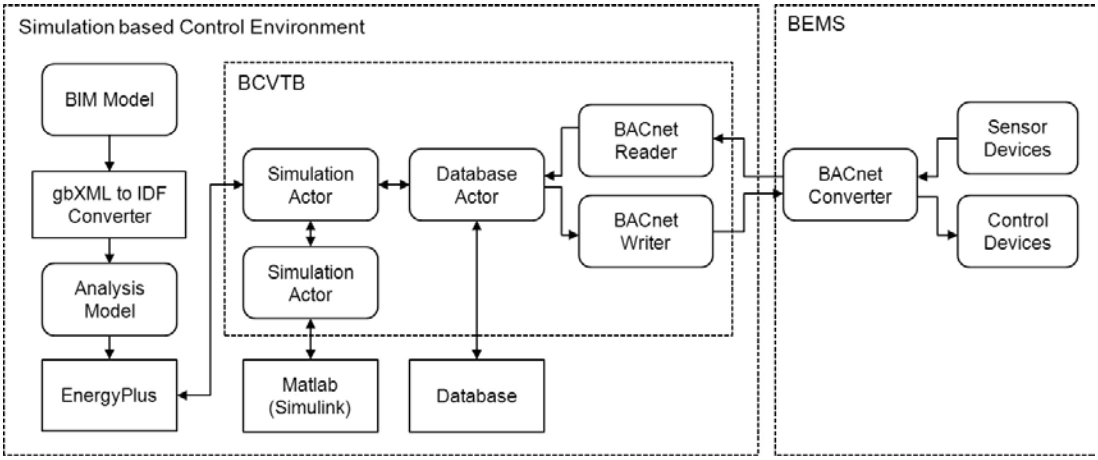

Figure 1. *A framework of a simulation-based control system in the operational stages*

This system enables a simulation based control through BCVTB. Key components to realize the simulation based control system are discussed below.

1) Establishment of an analysis model in the operational stage
An architectural BIM model is converted to a simulation model with additional information including actual HVAC system data, measured and monitored data from BEMS, weather data and information about Energy Management System (EMS).. EMS in EnergyPlus provides high-level, supervisory control to override selected aspects of EnergyPlus model. A programming language called EnergyPlus Runtime Language (Erl) is used to describe the control algorithms (DOE 2011). The External Interface in EnergyPlus allows coupling EnergyPlus with the Building Controls Virtual Test Bed (BCVTB).

2) Real-time monitoring and simulation
In order to import monitored data from existing buildings and to conduct simulations for performance evaluation, BCVTB is used as a middleware which provide connections among the monitoring and measurement devices (e.g. sensors, meters) and a simulation program (EnergyPlus). Currently, some modern buildings are equipped with BEMS that includes a wide range of monitoring, measurement and control systems. BEMS enabled with open protocols such as BACnet makes monitored data and control signals more accessible throughout various components and subsystems in a building. The BACnet reader actor in BCVTB can read data from BACnet devices. This actor requires a configuration file that specifies BACnet devices, the object types and the property identifiers with which data are to be exchanged (Nouidui 2011). The data received through the BACnet reader actor is sent to EnergyPlus using a simulation actor in BCVTB. The data information that is exchanged between the BCVTB and EnergyPlus is specified in a cfg file for variables.

3) Simulation based control
A simulation based control is performed with updated data from BEMS. After execute simulation at each time step, simulation result is being sent to BCVTB according to the description in the variables.cfg. The control signals from EnergyPlus simulation

are sent to the BACnet devices through the BACnet writer actor. At this point, the BACnet writer actor also requires a configuration file.

4) Database integration

The BCVTB supports the connection with a database through the database actor. The database stores monitored data from BEMS, simulation results from EnergyPlus, and control actions in the integrated system.

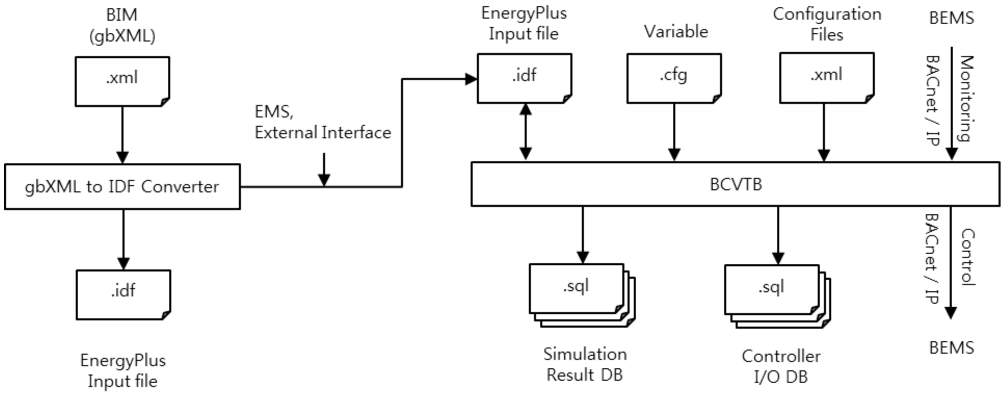

Figure 2. *Input/output data required for the simulation-based control system*

PROTOTYPE DEVELOPMENT

Building Information Modeling

A proof of concept demonstration has been conducted with a one zone model. The selected room was equipped with a packaged terminal air conditioner (PTAC) and an energy recovery ventilator (ERV). An architectural BIM model was created using RevitMEP2012 (Figure 3). Information required for energy simulation such as internal loads (people, lights, and equipment), set points, and schedules were entered according to a guidelines for residential buildings (Table 1).

Table 1. *Building operation data for the energy analysis model*

		Value	*Reference*
Number of people		4	-
Internal sources	People	131.8 W	(ASHRAE 2009)
	Lights	10.76 W/m^2	
	Equipment	6.5 W/ m^2	
Infiltration		0.3 ACH	(Chan 2004)
Heating setpoint		20℃	(Deru 2007)
Cooling setpoint		26℃	
Schedules	Occupancy	-	
	Lighting &Equip.		
	HVAC		
	Infiltration		

Analysis model in the operational stage

An analysis model for EnergyPlus was converted from the architectural BIM model using a gbXMLtoIDF converter (Moon et al. 2012). In addition, the information about the PTAC and ERV was entered in the analysis model according to the actual systems. The EMS module in EnergyPlus was constructed for a simulation based control system. The EMS sensors and controllers were modelled to set the zone CO_2 concentrations and the ERV ventilation system. An external interface module was included in the analysis model to exchange the data with BCVTB.

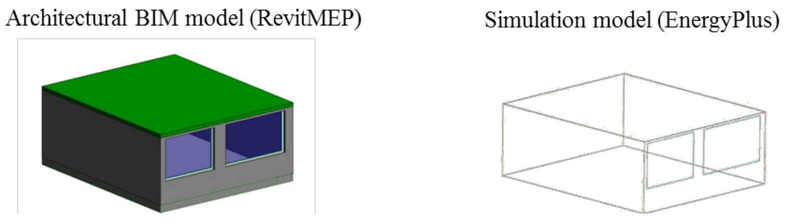

Figure 3. *An architectural BIM model and a corresponding analysis model*

Simulation based control using BCVTB

An integrated system for simulation based control using the BCVTB is shown in Figure 4. The process of a simulation based control is described below.

1) EnergyPlus → BCVTB: EnergyPlus conducts simulation at each time step (5 minutes). The simulation results (e.g., ERV control signals) from EMS at each time step are sent to the BCVTB using simulator actor.

2) BCVTB → ERV: BACnetWriter sends simulation results to the BACnet Converter through BACnet/IP. The control signals received from the BCVTB operates the ERV system.

3) ERV → BCVTB: the BACnetReader reads operation mode (on/off) from the ERV at each time step.

4) BCVTB → EnergyPlus: the ERV operation mode at a time step is sent to EnergyPlus through the simulator actor.

5) BCVTB → Database: A database manager and an actor called “SQL Statement” are used to send data to the database (e.g., PostgreSQL).

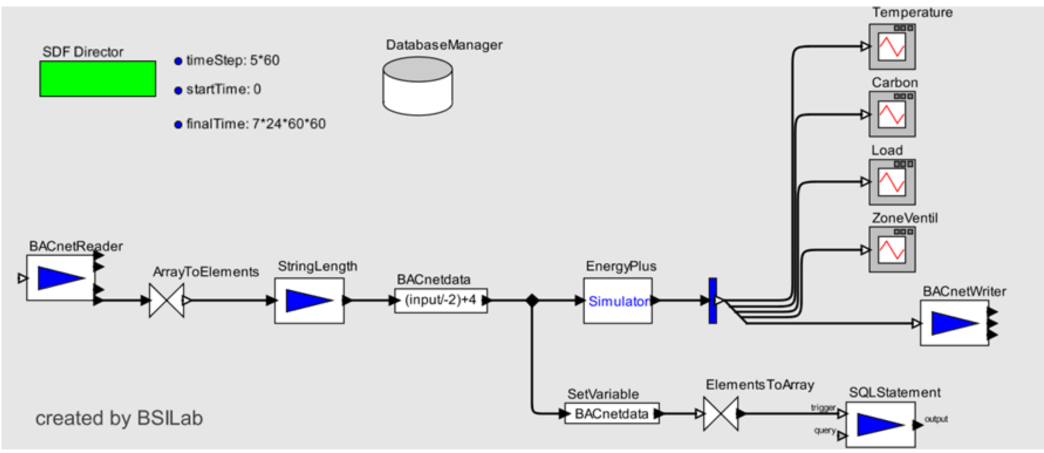

Figure 4. *Ptolemy II model for the integrated simulation based control in the BCVTB*

The simulation based control system first runs simulation in EnergyPlus and sends a control signal to the ERV system at each time step. The results from the simulation (EMS ventilation operation schedule) and the actual operation schedule of ERV system are shown in Figure 5. The results from the simulated EMS ventilator were reflected in the actual ventilator control with a 5 minute delay as expected.

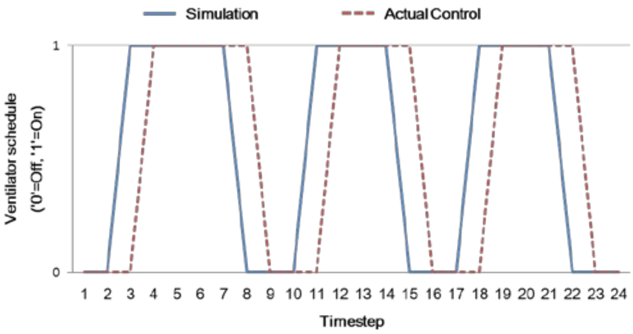

Figure 5. *Simulated ventilator schedule using EMS and actual operation schedule for ERV*

Case study

The developed simulation based control system is applied to a case study to evaluate potential energy savings in a residential building with a mechanical ventilation system. The ERV ventilation system was set to operate once the zone CO_2 concentration exceeds 1,000ppm. The results were compared with 3 control schemes with constant ventilation rates (0.3/0.5/0.7 ACH) for 24 hours. 0.5 ACH and 0.7 ACH are minimum ventilation requirements in residential buildings referring to the Japanese building code (BCJ 2011) and the Korean standard (MLTM 2009), respectively, In this case study, time step is set to 5 minutes and simulation period is a week with a constant outdoor CO_2 concentration of 400 ppm. The distributions of carbon dioxide concentrations from each control scheme are shown in Figure 6. CO_2 concentrations with ACH 0.7 did not exceed 1000ppm within the simulation period. On the other hand, CO_2 concentrations with 0.3 ACH and 0.5 ACH exceeded 1000 ppm for 11 hours and 8 hours per day, respectively. The simulation based control showed over 1000 ppm of the CO_2 concentrations on occasion during the occupancy period. The threshold level of CO_2 concentration in the system can be adjusted less than 1000 ppm to get lower CO_2 distribution. A shorter time step can be used to achieve lower CO_2 concentrations as well.

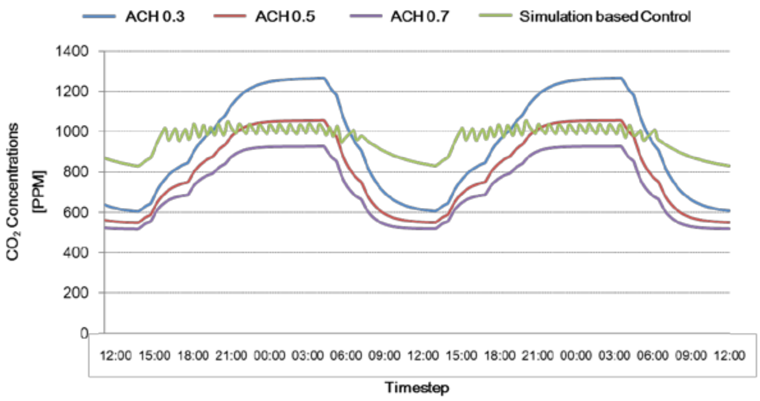

Figure 6*. CO_2 concentrations with simulation based control and constant ventilation rates*

Figure 7 shows the electric power consumptions from the ERV in the selected building. The simulation based control could reduce the energy consumption by 60% compared to a constant ventilation rate scheme with 0.7 ACH. Thus, the results from the case study supported that the simulation based control could provide energy efficient ventilation while maintaining appropriate indoor air quality.

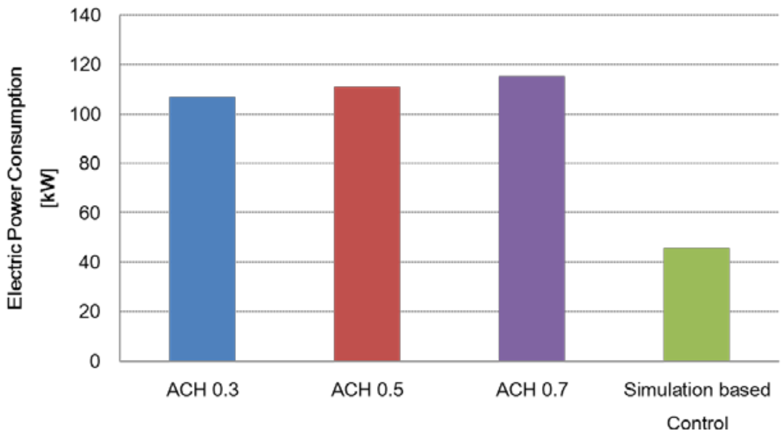

Figure 7. *Electric power consumptions from ERV*

DISCUSSION AND CONCLUSIONS

This study described a simulation based control system for BEMS using BCVTB and BIM connecting building information in the design stage and the operational stage. In this system an architectural BIM model can be used for an analysis model in the operational stage. The analysis model in the operational stage is enhanced with information from the actual HVAC systems and the EMS / external interface module in existing buildings. In addition, the analysis model is updated with measured and monitored data including weather data, occupancy schedules, lighting schedules, and so on. In order to realize the simulation based control, BCVTB is used as a middleware that connect BACnet devices, EnergyPlus and Database.

A prototype was developed and a case study was conducted to validate our approach. The key findings are summarized as follows.

An architectural BIM model can be used in the operational stage. This approach can reduce the modelling time efforts for building energy simulation and directly linked to a control system in the operational stage. A prototype of an integrated system with ERV was established through BCVTB and successfully implemented for simulation and controls. The case study showed that the simulation based control could provide energy efficient ventilation while maintaining appropriate indoor air quality.

As a future work, model-based control algorithms will be incorporated to realize a real-time simulation system for optimal control and operation in existing buildings.

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