Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

SMART BUILDING ENERGY MANAGEMENT SYSTEMS (BEMS) SIMULATION CONCEPTUAL FRAMEWORK

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ABSTRACT

Continuing growth of energy use by commercial buildings has created a need to develop innovative techniques to reduce and optimize building energy use. Recently Building Energy Management Systems (BEMS) have gained popularity because of increasing interest in building energy conservation and savings. In this study, a conceptual framework for real-time weather responsive control systems combined with BEMS is proposed to achieve model simulation based Smart BEMS. The proposed control system is developed using building energy control patterns, which are generated from the combinations of weather data changes. As a result, building energy use can be adjusted by, for example, using daylighting responsive controls for electrical lighting as well as by adjusting the HVAC operational schedule, in response to weather changes. To create control logics for model based Smart systems, BIM and Computational Fluid Dynamic (CFD) simulation are used to obtain material properties and to develop air flow operational algorithms, respectively.

1 INTRODUCTION

It is widely recognized that existing buildings often consume more energy than is necessary from the design intent (Mills 2011). An increase in awareness about critical energy use in the building sector stimulated public and academic attention to the need for improvement of building energy efficiency, and there are various efforts to develop energy efficient buildings. The primary objective of energy efficient buildings is energy conservation and reduction in building operation process by controlling energy consumption.

Particularly, in the commercial building sector in the U.S., energy for space conditions (heating and cooling) and lighting comprises more than half of total commercial building energy consumption (U.S. Department of Energy 2012). Therefore, saving electricity for HVAC (Heating, ventilation, and air conditioning) and lighting during the building operation phase, while maintaining occupants' comfort, can be one of the main strategies for the achievement of energy efficient buildings (Oldewurtel et al. 2012).

As the needs for energy savings and efficient energy use in the building operation stage is escalating, continuous control of building energy consumption, which is implemented by Building Energy Management System (BEMS), is important (Kolokotsa et al. 2009). The majority of BEMS are primarily applied to manage HVAC and lighting systems so as to achieve optimum indoor environmental quality by minimizing energy costs. Also, BEMS can be used to monitor energy use, to keep historical energy usage data, and to report buildings' performance and operation. More specifically, currently developed BEMS are primarily collecting building energy usage patterns, tracking real-time energy use intensity (EUI), and identifying abnormal energy consumption, without integrated building energy control systems. Moreover, most currently used BEMS are sensor and metering based monitoring system, which do not consider detailed building geometric information. Thus, predicting and analyzing building energy use for efficient building operation strategy are not available using current BEMS.

With consideration of BEMS functional scalability, many recent research studies about building energy performance have actively approached the following representative concepts:

1. Integration with building control system (Wong et al. 2010, Prívara et al. 2011, Široký et al. 2011, Oldewurtel et al. 2012, O'Neill et al. 2014, Heo et al. 2015).
2. Building Information Modeling (BIM) based building energy performance (O'Donnell et al. 2013, Dong et al. 2014, Moon and Choi 2014).

Integrating the BEMS with automatic or manual building control systems can adjust abnormal levels of energy use (e.g. upper level of set point). For example, if excessive energy use for the air conditioning of a specific room is detected, the integrated automatic or manual control system in the BEMS can adjust the air conditioning system in the affected room.

With the rapid advance of Information and Communication Technology (ICT) automatic building control system have become more popular. A data communication protocol for the buildings' automatic control network, the BACnet standard, is used to develop BEMS based automatic control system (O'Donnell et al. 2013).

BIM is also an integral part to develop advanced BEMS since BIM stores the buildings' geometric information, physical properties and component's information. Buildings' material and equipment (e.g. HVAC) properties can be used for estimating physical based energy performances. Therefore, BIM based BEMS is, potentially more reliable and accurate than metering based BEMS.

In addition to the described two BEMS concept, the latest research about building energy performance is focused on real-time energy management, not rule-based or historical data based. Real-time weather data and energy usage pattern will be collected and analyzed, then, an appropriate control system will be applied to dynamically optimize energy flow (Kang et al. 2014). Although this type of advanced BEMS operation increases its accuracy and reliability for calculating energy performances, the energy use set point is usually underestimated due to occupants' effects. The behavior of a building's occupants have a significant impact on the energy use patterns by disturbing room temperature and heating and cooling loads (Ryan and Sanquist 2012).

Taking into account the latest research directions about BEMS and advanced building energy performance, this study proposes a conceptual framework for model simulation based BEMS. More specifically, the proposed conceptual BEMS in this study is a real-time building energy simulation based BEMS including occupants' uncertainty. In this study, occupants' uncertain behavior is limited to the status of window's being open or closed.

2 DEVELOPMENT OF CONCEPTUAL FRAMEWORK

2.1 Language

The proposed conceptual framework for smart BEMS in this study, which includes real-time simulation based weather responsive control and occupants' impact, covers two dominant energy use control in buildings, daylighting and HVAC as shown in Figure 1.

Enclosed in the blue box is the daylight control workflow and in the red box is the heating and cooling control workflow. Information from BIM is used as geometric parameters for calculating lighting intensity and thermal performance of the room. And, 1-hour interval, real-time weather data including outdoor temperature and wind characteristics is collected from an on-site weather station or from weather web site. Also, a set point reference energy model is created using EnergyPlus representing design intent or calibrated acceptable energy performance to compare and evaluate current energy use pattern of the building.

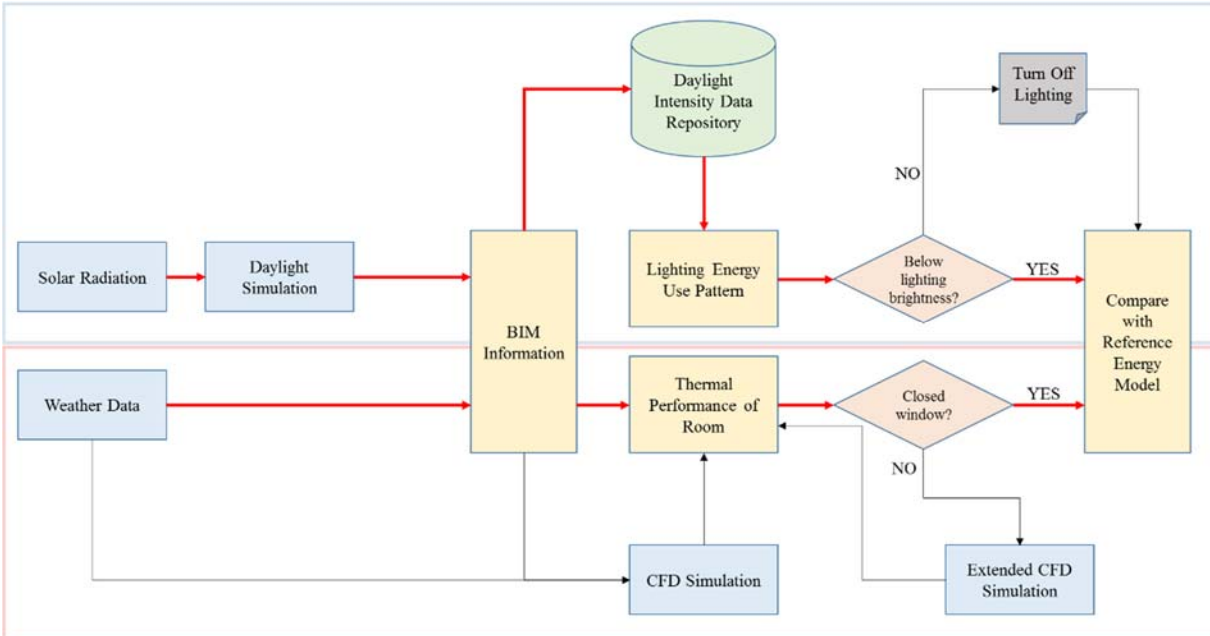

Figure 1: Smart BEMS Conceptual Framework.

2.2 Lighting Controlled BEMS

In order to implement lighting control, pre-defined daylight intensity by time variable is generated using a daylighting simulation tool such as Autodesk 3D Max Design, Daysim or Radiance. These tools are validated with experimental analysis (Reinhart and Breton 2009). Required data for the daylight intensity database can be collected from the BIM data such as the building's location, orientation and glazing properties. Generated hourly changing daylight intensity data is sent to database, called daylight intensity data repository. The proposed BEMS sends a query every hour to acquire the daylighting intensity pattern of the building. The selected hour daylighting intensity from repository is transferred, and then compared to current lighting energy usage pattern. If the space daylighting exceeds the artificial lighting brightness, the lighting control turns off the light in the selected space.

A lighting control simulation test was performed in this study using a simple office space unit BIM model. The area of the test unit model is 2000 ft^2 (40 ft by 50 ft), and it has a north faced curtain wall system. The hourly averaged transmitted daylighting intensity into the office room was simulated with following assumptions:

1. Sky condition is clear.
2. Model location is Gainesville, FL (Latitude: 29.6742° and Longitude: -82.3363°)
3. Reference office brightness is set as 2000 lux
4. Artificial lighting is installed horizontally with 10 ft. interval (i.e. 3 row) as shown in Figure 2.
5. Each row of artificial lighting is separately controlled.

An hourly daylighting simulation was conducted and the analysis results were generated as visual images and a spreadsheet as shown in Figure 3. The simulation was performed based on a normal office building schedule, 8 am to 5 pm, at 1 hour intervals on December 3rd, 2015. The daylighting intensity display image of each hour is generated by averaging 1-hour duration transmitted daylighting intensity. In addition, spreadsheet type result includes transient daylighting intensity at the simulation starting and ending time. Figure 3 illustrates the daylighting level of the proposed office space at 9 am, 1 pm, 3 pm, and 5 pm to identify excess lighting levels.

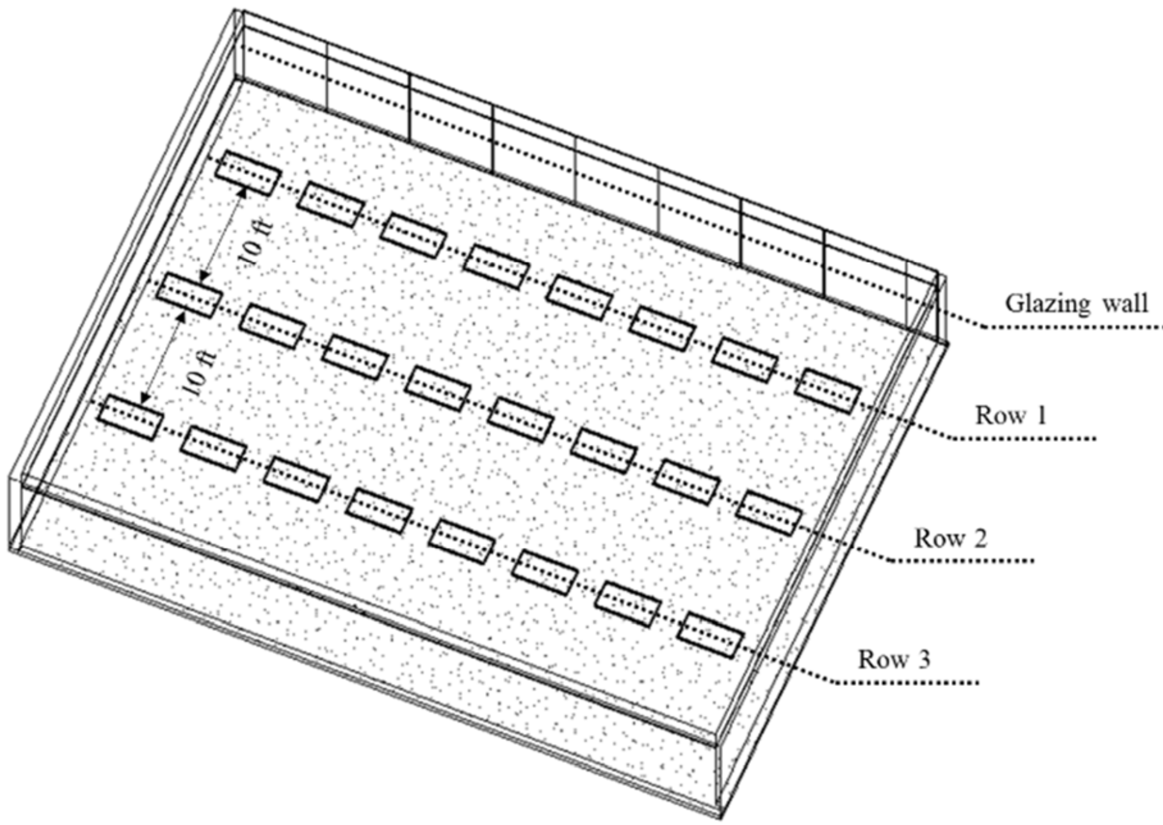

Figure 2: Top view of test office unit BIM model implemented 3 rowed ceiling lights.

As shown in Figure 3, from 1 pm to 3 pm, the illuminance level of the area around the glazing wall and "Row 1" exceeded 2000 lux and the daylighting illuminance level is decreased from 4 pm. Therefore, the "Row 1" lighting area would have enough illuminance level (> 2000 lux) without turning on "Row 1" ceiling lightings during 2 hours (1 to 3 pm). This simulation results will be applied to the proposed BEMS to control "Row 1" ceiling lights to turn off from 1 pm to 3 pm. Then ceiling lights will turn on again from 4 pm.

This simple test daylighting simulation is conducted using a simple office room unit model. In real practice, whole buildings' lighting simulation is required to apply the BEMS control. However, running a whole building lighting analysis will require substantial calculation time. Thus, implementing real-time lighting simulation to the proposed BEMS may not be practical. Consequently, this study proposes a daylighting intensity data repository concept. The daylighting illuminance levels for certain (e.g. maximum of 1 year) period are simulated using a BIM model, and the results will be organized by day and time, then it will be saved to the database. The proposed BEMS will use pre-developed daylighting data whenever starting operation.

The conducted lighting simulation assumed a clear sky condition. But, in real practice, the sky condition changes, and it is a significant factor affecting daylight intensity. Therefore, for more accurate lighting control, the effect of sky conditions on daylight intensity needs to be further evaluated. Developing a coefficient value for varied sky condition would be one of the simplest methods to apply into the proposed BEMS.

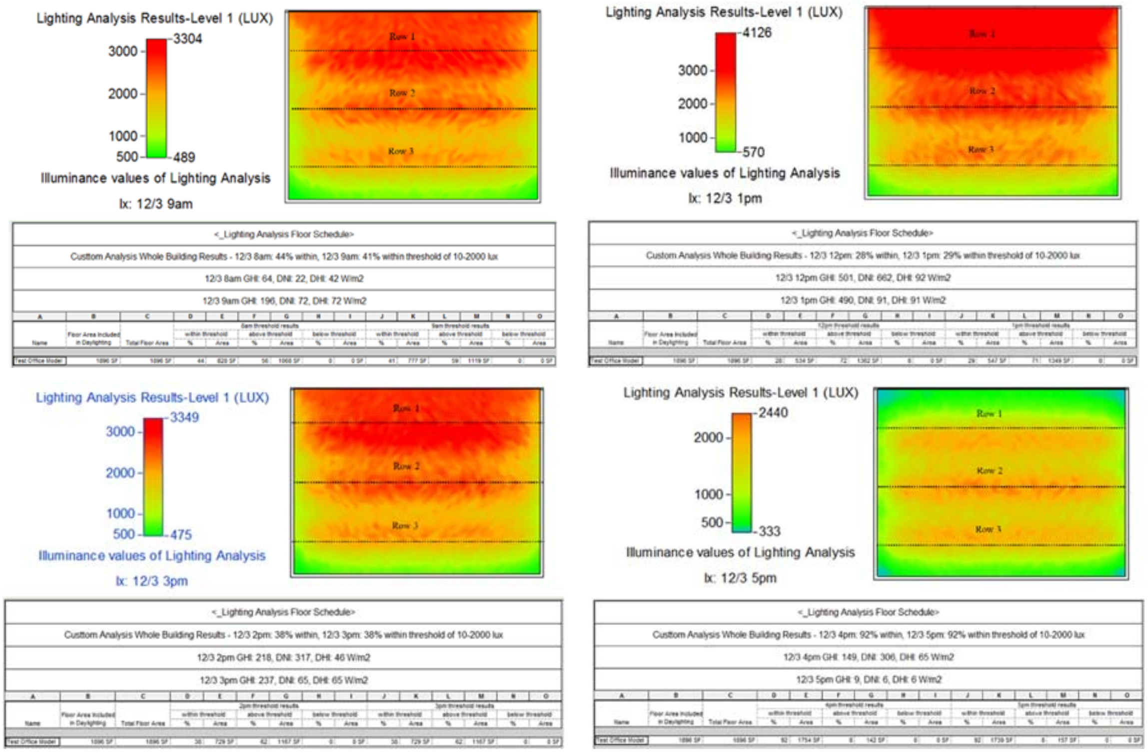

Figure 3: The simulation results of daylighting illuminance level at 9am, 1pm, 3pm, and 5pm for test office BIM model.

2.3 Heating and Cooling Controlled BEMS

Analyzing heating and cooling energy use requires a more complex analysis of the combined parametric effects on the buildings' thermal performances. The combined effects of real-time weather data, solar radiation intensity, and glazing properties on the thermal performance of a room needs to be carefully evaluated. Theoretically, thermal performance of the rooms in a building is determined by interactions of conduction, convection, and radiation. Investigating thermal interaction is not a trivial task. In order for fast and reliable thermal analysis, Computational Fluid Dynamic (CFD) techniques are used in this study. CFD simulation is a comprehensive tool to analyze thermal performance with consideration of thermal conduction, convection, and radiation. The results of CFD simulation have been validated in many research (Guardo et al. 2011, Kim et al. 2011, Mingotti et al. 2011, Radosavljevic et al. 2014, Ray et al. 2014).

For reliable CFD simulation in this study, building geometric information as parameters, which are independent of time, and outdoor weather condition including temperature with wind characteristics as time dependent variables are required. Building geometric parameters are extracted from the BIM data, and hourly changing outdoor weather condition is collected from an on-site weather station or weather website.

Since the proposed BEMS are designed to identify abnormal energy use within a certain time interval, the specified time interval for collecting real-time weather data and the duration of CFD simulation have to be set up. In this study, real-time weather data will be collected every hour starting from 10 minute before the building schedule. And, updated weather data for every hour is added to the CFD thermal performance simulation for the next hour. The conceptual BEMS schedule proposed in this study is shown in Figure 4. In addition to geometric and weather information, solar radiation intensity is one of the significant factors used to determine thermal performance of buildings' room. Analysis of the solar radiation effect of a room's thermal performance requires substantial calculation time. Therefore, in order to simplify the CFD based thermal simulation process, solar radiation intensity for developing heating and cooling control BEMS is preliminarily calculated using physical fundamentals of solar radiation as shown in Table 1. The

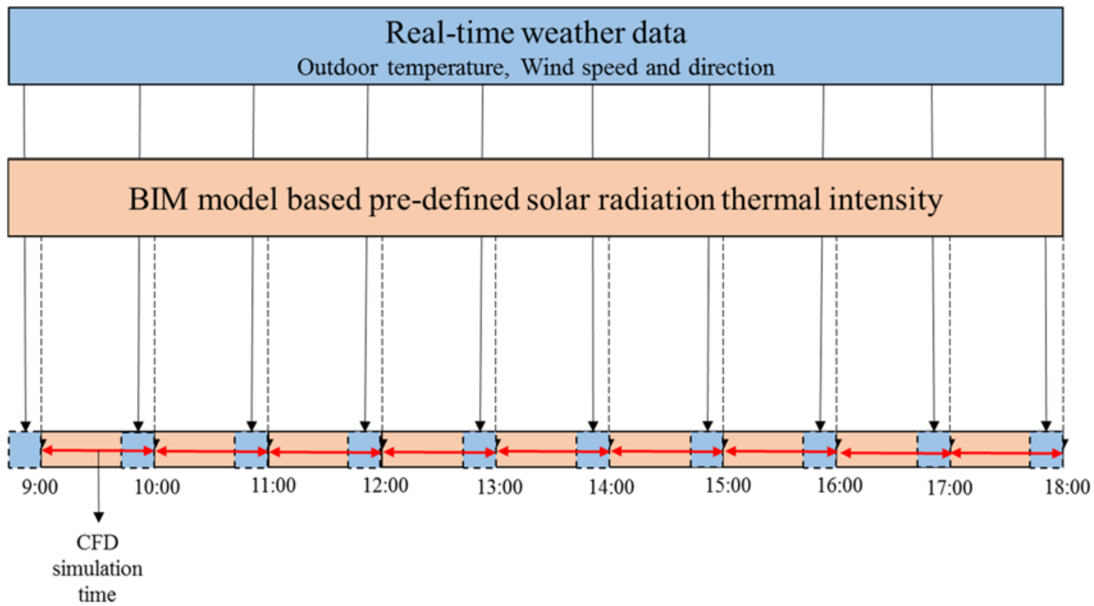

Figure 4: Proposed BEMS operation schedule.

Table 1: Hourly solar radiation intensity based on physical fundamentals.

Beam radiation (I_{bc}) + Sky diffuse radiation (I_{dc}) + Ground reflected radiation (I_{rc}) $\boldsymbol{S_T = I_{bc} + I_{dc} + I_{rc}}$	
$\boldsymbol{I_{bc} = C_n I e^{-k/\sin\alpha} * \cos i}$	C_n = clearness number (assuming the value of 1) I = extraterrestrial solar radiation k = atmospheric optical depth α = solar altitude angle i = angle of incidence
$\boldsymbol{I_{dc} = C(C_n I e^{-k/\sin\alpha})\cos^2(\beta/2)}$	C = sky diffuse factor β = wall angle
$\boldsymbol{I_{rc} = \rho C_n I e^{-k/\sin\alpha}(\sin\alpha + C)\sin^2(\beta/2)}$	ρ = ground reflection factor (0.2)

proposed BEMS is used to identify hourly thermal change of rooms in buildings, the data of hourly changing solar radiation intensity is also collected. More specifically, geometric BIM data including optical properties is applied for developing solar radiation intensity. The developed BIM accommodated solar radiation intensity presents the amount of heat energy. Consequently, variable solar intensity depending on outdoor and indoor temperature will be analyzed during the CFD simulation process. The workflow for this process is shown in Figure 5.

If window is opened by occupants who desire ventilation during the building operation schedule, analyzing thermal performance of the room would be more complicated due to consideration of the additional combined effect of air inflow to the room with a heating or cooling schedule. In general, air

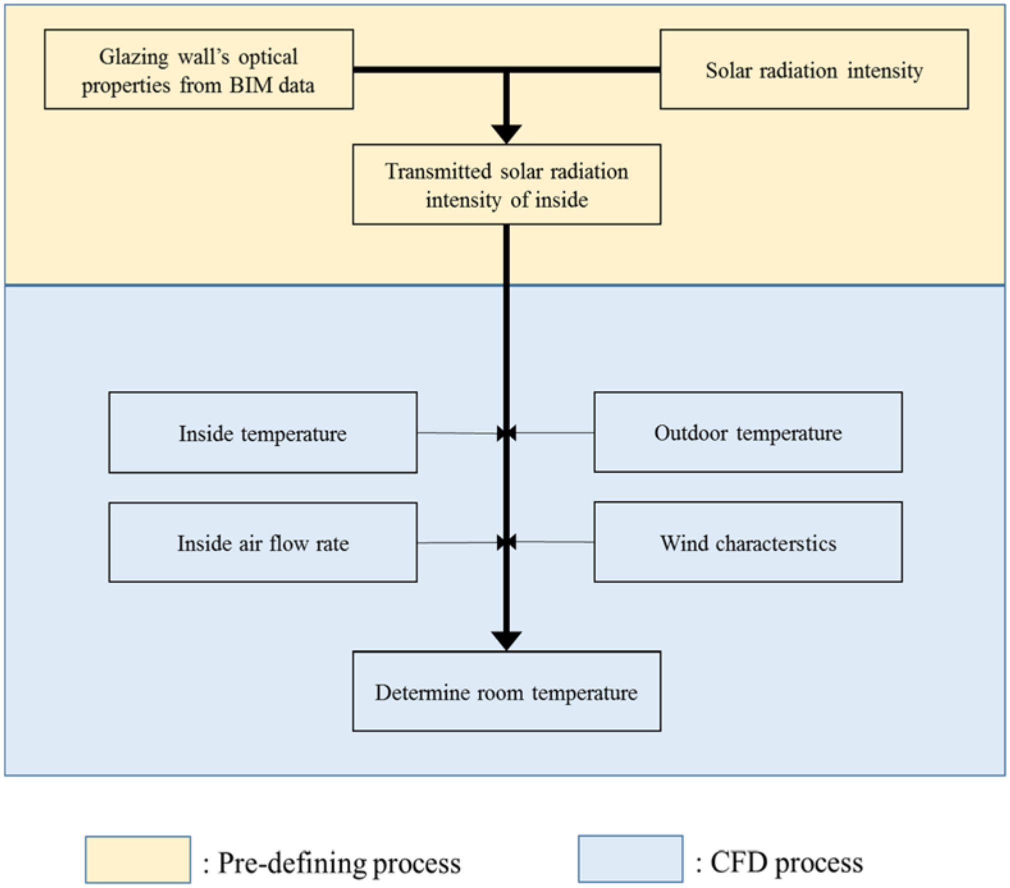

Figure 5: Schematic workflow for CFD process of proposed BEMS.

inflow from outside to the room circulate air flow movement resulting in room temperature change. Fluctuating room temperature results in an abnormal schedule for heating and cooling. In order to reduce room temperature fluctuation by the occupants' uncertain behavior, extended CFD simulation is used to control heating and cooling energy consumption for the case of opened windows. Extended CFD simulation in this study is a separate process because of the occurrence of different boundary condition for thermal analysis caused by the opened windows. By implementing a separated extended CFD simulation process for uncertain cases, the main CFD simulation process for the proposed BEMS will not disturbed.

In this study, the case of opened windows is detected by installed sensors, the room zonal information from BIM and real-time weather data are imported to extended CFD simulation to create new boundary conditions and run thermal analysis. Computed thermal performance result of an opened window room would be compared with targeted set point temperature. If the new result from extended CFD for an opened window room has a certain level of discrepancy with set point, heating and cooling equipment will be turned on to adjust room temperature.

3 CONCLUSION AND FUTURE RESEARCH

The research area of building energy performance management and control is rapidly expanding and advancing due to recent substantial energy conservation efforts in the building sector. Although several types of BEMS have been implemented in office buildings, the major functions of these types of BEMS are to monitor, collect, store, and report energy usage data without control systems. Recently developed BEMS have been integrated with automatic or manual control systems to prevent anomaly in energy consumption. Moreover, several types of BEMS integrated with BIM have been proposed by many researchers. Since

BIM data can be directly used for developing BEMS, more reliable and accurate evaluation would be enabled. Moreover, BIM data can be used for developing model predictive control (MPC) or simulation based control. Recently, as the capability and accuracy of BIM based simulations have significantly improved, developing real-time simulation based BEMS are more attractive.

With considering current improvements, this study focused on the feasibility of model simulation based BEMS development and proposed a conceptual framework for smart BEMS. The proposed advanced BEMS are limited to the features of lighting energy control and cooling and heating energy consumption. For lighting energy control, a daylighting intensity database is pre-constructed, and the data can be used to detect the space where artificial lighting can be turned off if transmitted daylighting intensity is higher than lighting brightness. In addition, in order to optimally control heating and cooling energy use, occupants' behaviors are included for developing advanced BEMS. In this study the occupants' uncertainty is considered as the desire of opening windows. If opened windows are detected by installed sensors, the opened room BIM data and real-time weather data are transferred to CFD simulation to create a new boundary condition. Newly created boundary conditions would be used for analyzing thermal performance of selected room; and the result from the CFD simulation can be compared with reference model to adjust room temperature.

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