Optimal Control of Operable Windows for Mixed Mode Building Simulation in EnergyPlus

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Abstract. A well-designed mixed mode building allows natural ventilation when the outside weather conditions are favorable and deploys air-conditioning when natural ventilation is not able to provide sufficient comfort. In this study, a methodology is proposed to enable real time control of operable windows for mixed mode ventilation building. EnergyPlus is used for building energy simulations. A real-time simulation is performed using Building Controls Virtual Test Bed (BCVTB). In this methodology, AERIS Weather Data is used to forecast hourly weather parameters. Seasonal Autoregressive Integrated Moving Average (SARIMA) Models are used to model a day-ahead prediction for the lighting load, electric load and the occupancy profiles. Co-simulation of EnergyPlus is carried out with BCVTB to enable real-time simulation wherein; the EnergyPlus weather file parameters and input building loads are updated every hour. Based on the indoor and outdoor conditions, EnergyPlus calculates the schedule for opening/closing of windows. A simulation based case study for Hyderabad, India is performed to demonstrate the working of the proposed methodology. Reduction of 25% in cooling energy demand was estimated in a mixed mode building as compared to the fully air-conditioned building during the study period.

1. Introduction

Mixed-mode buildings combine Natural Ventilation (NV) (through operable windows) and mechanical cooling systems to achieve sustainable comfort while attaining significant energy savings at the same time [1]. Operable windows can be operated either manually or automatically to provide natural ventilation in a building when the outside weather conditions are favorable. They can be closed when supplemental cooling through mechanical systems is required to achieve comfort. A good design of a mixed-mode building employs proper control strategies for integrated operation of operable windows and conventional mechanical cooling systems to achieve acceptable thermal comfort and reduce cooling loads [3].

Several experimental and simulation-based studies have been conducted to demonstrate the potential for deploying mixed-mode ventilation strategy in buildings. Zhai et al. simulated three real buildings and evaluated the airflow-thermal modeling in EnergyPlus [4]. Ezzeldin and Rees performed simulation case studies for different strategies of mixed-mode office buildings in arid climates with EnergyPlus.

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Significant plant savings of more than 40% was achieved by deploying natural ventilation when it is thermodynamically advantageous and active cooling systems when it is not [5]. Gandhi et al. identified approaches and tools for simulating mixed-mode buildings and analyzed them to understand the point of view of practitioners in simulating NV and mixed-mode buildings [6]. Wang and Greenberg employed EnergyManagementSystem (EMS) in EnergyPlus to simulate window operation type for different strategies for mixed-mode ventilation. The resulting control strategies for window operation are analyzed based on the criteria for thermal comfort and energy consumption [7]. A study performed by Sorgato et al. involved an application of a combination of HVAC system and natural ventilation in simulating a residential building in Brazil using EMS in EnergyPlus to analyze occupant behavior on overall building energy consumption. Low thermal emittance and medium thermal capacity resulted in energy savings of up to 32% in cooling [8]. Salcido et al. have performed a comprehensive literature review evaluating the potential of mixed-mode ventilation systems [9]. One of the most recent studies conducted by Pesic et al. evaluated the potential for natural and hybrid ventilation of the Mediterranean coastal region of Catalonia. “Climate Potential for natural ventilation” methodology was used to assess the availability of NV according to climatic conditions and EnergyPlus was later used to simulate hybrid ventilation and natural ventilation techniques for a low-rise office building model [10]. Chen et al. considered general uncertainties and different building control intelligence to evaluate the hybrid ventilation potential in different climates of US. Authors concluded that 10-50% of energy could be saved across the US if hybrid ventilation is deployed [11].

The topic of real-time control of operable windows for mixed-mode ventilation has not been explored thoroughly by building researchers. Model-predictive control strategies have been deployed for optimizing control strategies for window operation based on building energy simulation [12], [13]. The algorithms for deploying these control strategies are very computationally intensive and cannot be used real-time, rather they are known as offline MPC. Also, most of the research conducted on mixed-mode buildings has concluded that the operation of mixed mode buildings is very climate specific. Hence, it is important to carefully evaluate the potential for energy savings and thermal comfort for buildings of a particular climate. This work proposes a methodology for real-time optimal control of operable windows for mixed mode building energy simulation in EnergyPlus. Using this methodology, the potential for energy savings is evaluated for the climate of Hyderabad, India.

2. Methodology

2.1. Overview

A real-time building energy simulation is performed using BCVTB. The target building is modeled in EnergyPlus. Local weather forecast data is recorded every hour through AERIS Weather Data. A day ahead prediction is modeled for the lighting load, electric load and the occupancy profiles using Seasonal Autoregressive Integrated Moving Average (SARIMA) Models. Co-simulation of EnergyPlus is carried out with BCVTB to enable real-time simulation wherein; the epw weather file and the input building loads are updated every hour. According to indoor and outdoor weather conditions, EnergyPlus outputs the signal for opening/closing of windows. A flowchart for the present study is described in Figure 1 and Figure 2.

2.2. Seasonal ARIMA Model for Time Series Forecast

Introduced by Box and Jenkins in 1976, ARIMA is one of the most popular and frequently used models for stochastic time series prediction, especially for forecasting univariate time series data. ARIMA (p, d, q) originated from Autoregressive model (AR), Moving Average model (MA), and the combination of both AR and MA, ARMA Models. Parameters (p, d, q) stand for non-negative integers that refer to the order of the autoregressive, integrated, and moving average parts of the model respectively.
Box and Jenkins generalized ARIMA \((p, d, q)\) model to incorporate seasonal changes (including monthly, quarterly and degree of weeks change), which led to seasonal ARIMA model, abbreviated as SARIMA \((p, d, q)\) \((P, D, Q)\). Parameters \((P, D, Q)\) are the seasonal autoregressive, seasonal integrated and seasonal moving average parts of the model respectively and \(s\) corresponds to seasonal period. More detailed theoretical aspects of the models are included in [14].

The evaluation criteria for measuring the prediction accuracy of SARIMA models are based on Mean Absolute Percentage Error (MAPE). MAPE quantifies the percentage of average absolute error occurred between forecasted values \((f_t)\) and original values \((y_t)\) as in

\[
\text{MAPE} = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{y_t - f_t}{y_t} \right| \times 100
\]  

In the current study, SARIMA model has been implemented in R to predict the following:

- Short-term global solar radiation using last 2 weeks half-hourly data from AERIS Weather Website for one day in advance.
- Lighting load, plug load, and occupancy profile using last 2 weeks hourly data from their corresponding sensors for one day in advance.

2.3. Weather File Generation

An EPW weather file in EnergyPlus consists of 29 weather elements. Out of these, only 13 elements are used for building simulation (EnergyPlus Documentation). These include dry bulb temperature, relative humidity, dew point temperature, wind speed, wind direction, sky cover, precipitation, direct solar radiation, and diffuse radiation. Except for the values for diffuse and direct solar radiation, all the other weather forecast values for every hour are logged from AERIS Weather Website using the API provided by the website (Anon. A). Validation for the accuracy of weather prediction is done using the Coefficient of Variation for Root Mean Square Error (\(C_v(RMSE)\)). RMSE measures the spread of the deviation of forecasted values from the original values, whereas \(C_v(RMSE)\) is a normalized measure of uncertainty between actual and forecasted values as defined by:

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{t=1}^{n} (y_t - f_t)^2}
\]
\begin{equation}
C_v(RMSE) = \frac{RMSE}{\bar{y}} * 100
\end{equation}

Where \( \bar{y} \) is the mean of measured weather variable.

As mentioned in the previous sub-section, short term global solar radiation values are forecasted using the SARIMA model using last 2 weeks half-hourly data from AERIS Weather Website. The values of both direct normal and diffuse horizontal radiation are required to generate an EPW weather file. The decomposition of global solar radiation into direct and diffuse radiation is done using the model proposed by [17].

### 2.4. Control Strategy for Modeling in EnergyPlus and Co-Simulation with BCVTB

The target building is modeled in EnergyPlus. EnergyPlus models mixed mode ventilation through Availability Manager for Hybrid Ventilation. This availability manager estimates the cooling load for the simulation time step based on outside temperature/enthalpy, zone temperature, and setpoint. The challenge lies in the fact that EnergyPlus doesn’t consider the change in SHGC because of the opening of windows. As a result, zone temperatures are being underestimated because low SHGC is being considered.

To overcome this, the building is simulated for NV mode for the next hour for which window schedule is to be estimated. A 30-day pre-simulation period is required for proper warm-up of the building. Based on the simulation results, we use air-conditioning (AC) when the temperature and humidity levels cross the comfort barrier in NV. For current paper, favorable conditions for the opening of windows comprise of zone air temperature less than 26 deg C and zone relative humidity less than 80 %.

The simulation continues for the next hour if NV is able to maintain favorable conditions, otherwise it is stopped and schedule of AC is updated to “ON” for the next hour. To compensate for the change in SHGC, an EnergyManagementSystem (EMS) object is used which changes the construction state of the window to increase its SHGC to 0.9 when a window is signaled to open by EnergyPlus. This control algorithm ensures proper estimation of zone temperatures and solar radiation entering through the windows, unlike the Availability Manager for Hybrid Ventilation available directly in EnergyPlus.

EnergyPlus is co-simulated with BCVTB to achieve real-time control. It is possible to synchronize the simulation time of BCVTB to real time, which enables real-time simulation. Real-time dynamic EnergyPlus input variables in the form of weather data, lighting load, plug loads and occupancy profiles (as obtained using the above sub-sections) – are combined in BCVTB [18]. Weather data according to the forecasted weather, lighting load, plug loads and occupancy data (through SARIMA models) are updated every hour. All the updated data are fed into EnergyPlus using the co-simulation interface provided by the BCVTB and accordingly, EnergyPlus calculates the schedule for window opening/closing internally.

### 3. Simulation Case Study and Results

Building energy simulation is performed wherein; a single zone office model is developed in EnergyPlus V8.9. The building model has an area of 75 m² and follows the 24-hour occupancy schedule. The simulation model represents the conventional construction practices of India as shown in Table 1. Ideal Loads Air System is operated for air-conditioning. AirflowNetwork objects are used for modeling natural ventilation. All the experiments are performed for the working days of 9th to 13th July for Hyderabad climate.
Table 1 Building Model Description

| Model Properties | Value       |
|------------------|-------------|
| Wall U-Value     | 2.014 W/m²·K |
| Roof U-Value     | 3.911 W/m²·K |
| Glass SHGC       | 0.25        |
| Glass U-Value    | 3.3 W/m²·K  |
| LPD              | 10.8 W/m²   |
| EPD              | 16.7 W/m²   |
| WWR              | 30%         |
| Occupancy        | 10 m² per person |

Table 2 MAPE Scores for Load Prediction

| Type of Load Prediction | MAPE |
|-------------------------|------|
| Lighting Load           | 4.8% |
| Plug Load               | 4.3% |
| Global Horizontal Solar Radiation | 15% |
| Occupancy               | 3.2% |

Table 3 Validation for Weather Forecast

| Weather forecast element | C_v(RMSE) |
|--------------------------|-----------|
| Outside temperature (°C) | 4.5%      |
| Relative Humidity        | 16.5%     |
| Dew Point Temperature    | 13.5%     |

A simulated schedule for lighting load, plug load, and occupancy profile are taken from [19]. Faults were introduced in the 3 input parameters by replacing their original values to another value within a tolerance of 20%. SARIMA Model was trained on a 2-week hourly data, from 25th June to 8th July, to predict the three parameters for the next day of 9th July. The results of the SARIMA model on lighting load and electric load are shown in Figure 3 and Figure 4 respectively, wherein the blue section represents the prediction on the 15th day based on the data from the last 14 days. The MAPE validation for the SARIMA model is done for the 3 input variables with respect to original data without faults, and their validation scores are presented in Table 2.

![Figure 3. Electric load forecast profile](image)

![Figure 4. Lighting load forecast profile](image)

Weather forecast elements are logged from AERIS Weather Website for 9th to 13th July. The C_v(RMSE) scores for outside temperature, relative humidity, and wind speed when compared with their corresponding actual values are depicted in Table 3.

The global solar radiation is predicted in the same way as the lighting load, plug loads and the occupancy profiles. It is decomposed into direct normal and diffuse normal radiation as described in the sub-section of Weather File Generation as described in the previous section.

All the real-time dynamic EnergyPlus variables mentioned above, are combined in BCVTB and an interface for co-simulation is developed with EnergyPlus. This mixed-mode building energy co-simulation, based on real-time weather data, was performed from 9th to 13th July for Hyderabad. At the same time, simulation was performed for fully air-conditioned mode for the 5 days. Mixed-mode simulation saved 25% cooling energy demand when compared to a fully air-conditioned simulation. Best results were found for 12th July when a reduction of 77% was observed in cooling energy demand by
running building in mixed-mode, as shown in Figure 5. Also, profiles for zone air temperature and zone relative humidity are depicted in Figures 6(a) and 6(b) respectively for the same day.

![Figure 5 Comparison of Cooling Energy Demand for 12th July](image)

**Figure 5** Comparison of cooling energy demand between mixed-mode and AC building

![Figure 6 Comparison of Zone Air Temperature (a) and Zone Relative Humidity (b) for 12th July](image)

**Figure 6** Comparison of Zone Air Temperature (a) and Zone Relative Humidity (b) for 12th July

### 4. Conclusions

The current study proposed a methodology for real-time control of operable windows in a mixed-mode building. A simulation case study was performed, and the potential for reduction in cooling energy demand has been presented for Hyderabad climate. Dynamic weather forecast data was logged from AERIS website every hour within $C_r$ (RMSE) of 20%. SARIMA models were successfully used to predict the day-ahead lighting load, plug loads, occupancy and global horizontal solar radiation within MAPE criteria of 15%. A co-simulation of EnergyPlus and BCVTB was performed using real-time input variables, and an optimal schedule for control of operable windows was obtained. Reduction of 25% in cooling energy demand was observed in a mixed mode building as compared to fully AC building during
the study period. Thus, the study concludes that a mixed-mode building provides better energy savings than a fully AC building while maintaining acceptable indoor conditions.

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