Hybrid Ventilation Potential Investigation for Small and Medium Office Buildings in Different US Climates Under Uncertainties

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Abstract

Hybrid ventilation, or mixed mode ventilation, is a technique that uses a mixture of natural and mechanical ventilation for maintaining a thermally comfortable indoor environment for building occupants. With its potential for improving both the energy efficiency and occupants comfort at the same time, its real application benefits across different US climate zones are still not clear, especially considering the possible variations of building context and building properties in real scenarios. In this paper, by taking these uncertainties into account, we have investigated the potential of utilizing hybrid ventilation on small to medium size commercial buildings across different US climate zones. One prototypical small to medium size office building was selected first. Uncertainties related to meteorology, building microclimate, building properties and operation have been applied for a thorough investigation of hybrid ventilation potential based on our baseline building. A rule based control has been specified based on the adaptive thermal comfort model in the thermal comfort standard. The results showed that the mean energy saving varies from 17% to 43.8% in different climate zones in US.

Keywords –

Hybrid Ventilation; Potential Investigation; Uncertainty Analysis;

1 Introduction

Air conditioning has long been recognized as one of the major sources of energy consumption during the operation of commercial buildings. Accompanying with the benefits such as stable and relatively comfortable indoor environment, the air conditioning system could also possibly bring some healthy problems such as sick building syndrome due to insufficient ventilation. On the other hand, naturally ventilated building, which is able to provide sufficiently large amount of fresh air, has become an increasingly popular option that is recognized by owners for moving towards greener building these years. However, it also suffers from constraints such as uncertain performance during the building operation due to its susceptibility to outdoor environment. As a compromise of both types of buildings, hybrid ventilation building has the capability of providing a comfortable indoor environment with sufficient ventilation in an energy-efficient way compared to air conditioned buildings. Meanwhile, it's more reliable than naturally ventilated building when maintaining indoor environment comfortable since it has the capability to transfer into air conditioned mode when the outdoor climate is not favorable.

Recognizing its benefits, some hybrid ventilation buildings were already established in Europe as pioneer studies [1]. For example, in Belgium, a small office building with 1500 m^2 area utilized large louvers on different façades for summer cooling while a small mechanical cooling unit was also installed to reduce the supply air temperature when the outdoor air temperature is too high. Based on the feedbacks, the ventilation system achieved good performance except in one office that got severest exposure to the sun. Also, in Italy, a four stories open plan office buildings with approximately 45 occupants were equipped with both natural ventilation system and a fan coil system for both summer cooling and winter heating. Similar buildings also exist in Denmark, Sweden, Norway etc. However, in United States, hybrid ventilation buildings are still rarely seen. One example of this type of building is San Francisco Federal building. Air conditioning is utilized at the lower floors of the building while upper floors are cross ventilated. Nevertheless, despite its excellent expected performance, the building suffers from large amount of complains ranging from thermal comfort to acoustics [2].

As the first step to popularize hybrid ventilation building in US, its application potential in different US climate zones for saving energy and improving indoor environment should be thoroughly investigated. As one of the most widely used techniques for assessing building performance, building simulation is an important tool in potential investigation of hybrid ventilation due to its reliability. Nonetheless, currently almost all the potential investigations of hybrid ventilation are still based on deterministic building simulation results, which could be insufficient to account for possible variations spring from simulation scenarios [3]. Thus, in this paper, different level of uncertainties in building simulation, ranging from meteorological, microclimate, building properties and operation scenarios, are quantified and discussed first. The hybrid ventilation potentials are then investigated based on our prototypical small to medium office building using the uncertainties we have quantified. The results of potential investigation will finally be presented. The following sections will be structured as follows:

2 Literature Review

Uncertainties in building simulation have been investigated by researchers for years. According to [4], the uncertainties could be categorized as structural uncertainty and parameter uncertainty. In the building simulation field, structural uncertainty represents the simulation inadequacy that springs from the simplified physical modeling process. A good example of this category of uncertainty is shown by Han et al [5]. In the paper, different methodologies such as computational fluid dynamics and default modeling in EnergyPlus have been compared. The results showed that the accuracy of energy simulation could increase up to 11% in certain cases. Also, Yuming et al [6] have quantified the solar diffuse irradiation uncertainty of Perez Model on the inclined surface based on real measurement data. A two-phase regression model was developed and the validation result showed that the model bias error could be reduced by this newly introduced model. In addition to the structural uncertainty, parametric uncertainty, which is caused by insufficiency of building information in the design phase, is also an important uncertainty source to consider. For example, the properties of construction material are one of the critical inputs for building simulation. However, they are rarely known before the construction process, which might cause large deviations of results in the modeling process. In order to address this deficiency, Domínguez-Munoz et al [7] have done an investigation about the variations of thermal conductivity and density for most of the mainstream construction materials. Similarly, to fully account for the inaccuracy of convection heat transfer, Palyvos [8] have summarized and provided a critical discussion on all the available correlations of external wind coefficients. Also, Thevenard and Haddad [9] have compared results from two building simulation models, in which one of them used typical reflectance for meteorological years while the other use actual recorded data. The results show that the difference could be up to 10.9% on yearly basis while 23.3% on a monthly basis.

However, despite of the existence of uncertainties that could have non-negligible impacts on the simulation outcomes, almost all the hybrid ventilation potential investigations are based on deterministic simulation results. Ezzeldin and Rees [10] have done a systematic investigation of hybrid ventilation potential in arid climates. In addition to basic hybrid ventilation strategy, the authors have also combined hybrid ventilation with other potential energy saving techniques such as evaporative, radiant or ground cooling. Deterministic simulations were implemented for representative cities in the arid climates. The conclusion showed that the energy saving could be up to 90% after combining the technologies. Also, Emmerich [11] has utilized a coupled multi-zone airflow simulation tool – CONTAMR to model a 5-story building in five representative cities in U.S. The results confirmed that the hybrid ventilation system could reduce energy consumption compared with mechanical system while maintaining the satisfactory indoor environment. Thus, considering the possible deviations that could be caused by building simulation uncertainties mentioned above, a more thorough investigation of hybrid ventilation potential taking fully account of all the possible variations of meteorology, building microclimates, properties and operations is needed to provide more reliable information of actual hybrid ventilation across different climates.

3 Methodology

3.1 Research Objective and Summary

Overall, the main objective of this research is to investigate the hybrid ventilation potential across different climate zones of U.S. with the different uncertainties presented thus to provide a more reliable and informative reference for the potential saving of hybrid ventilation. In order to achieve the goal, a representative building model will be selected first. The uncertainties from different levels will then be quantified and applied in our building simulation. The GURA workbench, which is specially designed for uncertainty analysis for building simulation, will be used to automate the process. The results and discussions will finally be presented.

3.2 Building Model

Considering the diverse types of zones including lobbies, office rooms etc., a campus building, whose layout is shown in Figure 1 below, has been selected as our baseline commercial building in the hybrid ventilation potential investigation. The whole building is composed of 21 zones with the detailed construction information listed in the Table 1 below. As to building operation related parameters, the lighting, electric equipment and occupancy are set to 8.5 W/m2, 8 W/m2 and 0.05 person/m2 respectively based on recommendations by ASHRAE [12]. And their schedules are also based on typical settings of commercial buildings in the ASHRAE guideline [13]. In addition, each zone has at least one window (2.1m * 2.4m) attached to meet the requirements of ASHRAE Standard 62.1 [14] for ventilation purpose in natural ventilation mode. Lastly, the HVAC system of the building was configured according to the recommendation of DOE reference commercial building [15]. Thus, VAV (Variable Air Volume) system was attached. The COP (coefficient of performance) for cooling was set to 3.4 while the efficiency of heating was set as 0.8. The supply air temperature from air conditioning unit was constantly 15℃ throughout the year. Air economizer was also used to adjust the outdoor air inflow rate based on the outdoor dry bulb temperature.

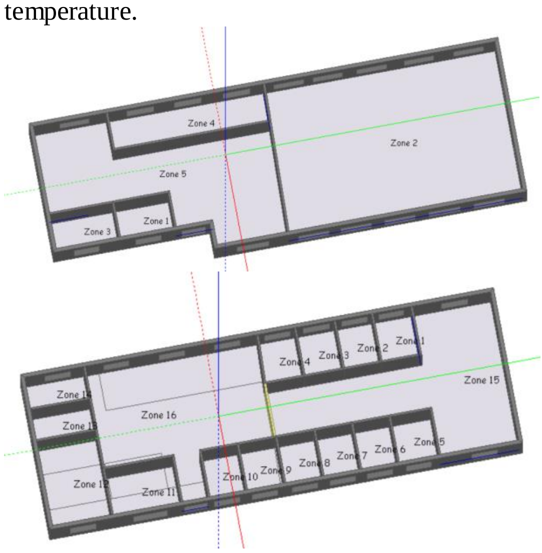

Figure 1. Baseline Building Layout

Table 1. Building Construction Details

Exterior Wall	U Value: 0.55 W/m^2-K Brick: 5 cm, Concrete Block: 10 cm, Rigid Insulation: 5cm, Gypsum Plasterboard: 1.3cm
Ground Floor	U Value: 1.96 W/m^2-K Concrete Slab: 15 cm
Roof	U Value: 0.73 W/m^2-K Bitumen Layer: 1 cm, Rigid Insulation: 4 cm, Cast Concrete: 12 cm, Plasterboard: 1.3 cm
Window	U Value: 2 W/m^2-K SHGC: 0.55

3.3 Uncertainty Quantification

3.3.1 Overall Setting

To efficiently uncover the potential of hybrid ventilation in different climates in US, a robust and thorough uncertainty quantification is essential. Since the purpose of this paper is for general investigation of hybrid ventilation potential, it is assumed that no further building context information is available such that a general version of uncertainty analysis is applied. More specifically, the uncertainties could be divided into 5 scales, i.e. meteorological uncertainty, urban uncertainty, building uncertainty, system uncertainty and occupant uncertainty. In our analysis, all the uncertainties from different levels are more or less considered. The detailed uncertainty quantification processes will be provided from Section 3.3.2 to Section 3.3.5 below. All the works are based on model discrepancy of EnergyPlus, which is the building simulation software we use for simulation.

3.3.2 Meteorological Uncertainty

Meteorological uncertainty depicts the uncertainties cause by variability of overall weather condition on one area or possible long term climate changes. Weather file is doubtlessly reported as one of the most critical inputs for the building simulation. However, currently in the building simulation practice, almost all the building modelers would only use TMY (typical meteorological year) or TRY (test reference year), which leads to the negligence of influence cause by possible weather fluctuations in that area. Accordingly, in our work, instead of using TMY, historical meteorological years are used as replacements in order to thoroughly investigate the potential and performance of hybrid ventilation under different weather conditions. 10 years have been randomly selected from 30 years historical meteorological years data and used as inputs for our simulation.

3.3.3 Urban Uncertainty

The urban uncertainty, or microclimate uncertainty, represents the possiblily different influence of building microclimate on the building simulation. Obviously, the microclimate around one building could be very different from the other (e.g. suburb vs. downtown) in real scenarios. However, most of these effects are still neglected in the building simulation. In our study, the influence of urban heat island effect (UHI), local wind speed and ground reflectance have been quantified and applied to generate better simulation results compared to deterministic simulation.

3.3.3.1 Uncertainty Quantification for Urban Heat Island Effect

Urban heat island effect, which commonly exists in most of large cities around the world, is one of the most important phenomenon to consider to achieve more accurate hybrid ventilation investigation results due to its influential impacts on the surround outdoor temperature of a building. In our works for urban heat island effect quantification, the high-fidelity TEB (tower energy budget) model was used to compute the temperature difference Δ_T between urban and rural area at the first place. Then, a statistical model is developed for prediction of Δ_T based on the weather condition at certain time steps. The equation is shown below:

$$\Delta_T = \beta_0 + \sum_{i=1}^{6} \beta_i w_i + \beta_7 T_r$$

in which $w = (w_1, .., w_6)$ are short wave and long wave solar radiation, air temperature, wind speed, pressure and specific humidity respectively and T_r is rural temperature. These parameters can all be generated from the weather data at the simulation time step. Since the microclimate of a building is uncertain, our inputs for TEB model vary from case to case to generate different sets of possible Δ_T under different scenarios. All the inputs including canyon height, canyon ratio, pervious road fraction and building roof area fraction for TEB model are based on a global database for urban geometric parameters [16]. Finally, a Gaussian process [17] emulator $\hat{\beta}(z)$ was established for the prediction of β under different scenarios.

3.3.3.2 Uncertainty Quantification for Local Wind

Local wind speed around the building is one of the most unpredictable variables in the building simulation. To quantify the uncertainty of local wind speed, the high fidelity model Community Land Model (CLM) [] was employed. Similar to the uncertainty quantification for urban heat island effect, the difference between the results of CLM and EnergyPlus prediction were calculated under different settings shown in Table 2 below. Piecewise linear regression was used as regression model,

$$\Delta_W = \begin{cases} \beta_{01} + \beta_{11} z + \xi & \xi \in N(0,\sigma^2) \quad when\ z < \tau \\ \beta_{02} + \beta_{12} z + \xi & \xi \in N(0,\sigma^2) \quad when\ z \geq \tau \end{cases}$$

in which z is the central height of building surface in order to further account for the variation of wind at different heights. All the coefficients in piecewise linear regression were estimated using maximum likelihood method. In our uncertainty quantification process, for all the experiment settings, the R square of regression was above 95%, which means that the uncertainties of wind speed were sufficiently quantified.

Table 2. Experiment Settings for Local Wind Uncertainty Quantification

	H		H/W		B_L/B_W	
	Min	Max	Min	Max	Min	Max
Country	3	3	0	0.3	0.25	1
Urban	99 cases from database				0.25	1
Cities	26 cases from database				0.25	1

3.3.3.3 Uncertainty Quantification for Ground Reflectance

Lastly, as one of the aspects of microclimate uncertainty, the uncertainty of ground reflectance was quantified in city, urban/suburban and open country areas. The equation below shows the calculation of ground reflectance from $f_{pervious}$ (the road area fraction of pervious road) and $\rho_{pervious}$ (pervious road solar reflectance).

$$\rho_{ground} = \rho_{pervious} f_{pervious} + \rho_{impervious}(1 - f_{pervious})$$

Monte Carlo method was utilized in the sampling process based on the data from [18].

3.3.4 Building Uncertainty

In addition to the meteorological and urban level uncertainty, building uncertainty is another significant source of uncertainties that could impose non-negligible impacts on the simulation outcomes. In our uncertainty analysis, for the building level uncertainty, mainly the material uncertainty and convection uncertainty were taken into account.

Building material uncertainty could be caused by many reasons such as different manufacturing and construction process, possible change of material property in specific environments etc. With respect to this uncertainty, one of the most thorough works was done by Domínguez-Munoz et al [7], in which all the uncertainties of thermal conductivity and density for mainstream construction material were quantified. In our uncertainty analysis, a relative normal distribution with 10% variance was applied to conductivity of window, density of normal construction material and solar transmittance of the window etc. Meanwhile, a relative normal distribution with 5% variance was imposed for material properties such as conductivity of normal construction material, front and back side visible light transmittance etc.

Except for the material uncertainty, uncertainties exist in building convective heat transfer also plays significant roles in the building simulation.

To sufficiently quantify the possible variations of convective heat transfer coefficient, firstly, literature surveys have been done to collect the results from different experiments. Using the following equation to calculate the external convective heat transfer coefficient,

$$h_c = aV_z + b$$

bivariate kernel density estimator was employed to model and estimate the density and covariance of a and b based on collected experiment results (V_z is the local wind speed). Lastly, optimization technique was utilized to determine the bandwidth H matrix for the kernel.

3.3.5 Building Operation Uncertainty

Last but not least, the uncertainties exist in the building operation, including uncertainty of lighting consumption, electric equipment consumption and occupancy consumption, are also significant to consider for an accurate prediction of the building energy consumption and indoor thermal environment. These related parameters are also the hardest parameters to accurately determine in the design phase of a building. However, due to the lack of related data, their uncertainties are usually not quantified for the simulation practice. In our uncertainty analysis, relative normal distribution with 30% variance were applied for both lighting usage density and occupancy density respectively for illustration purposes. Also, according to the ASHRAE fundamental handbook [19] for electric equipment consumption in the office with light and heavy office works, the possible variation of electric equipment consumption was set to uniformly distributed from 5.4 W/m2 to 16.1 W/m2 in our study.

3.3.6 Uncertainty Distribution

To efficiently distribute the uncertain parameter, the GURA (Georgia Tech Uncertainty and Risk Analysis) workbench was developed to automate this process. The process of conducting uncertainty analysis using GURA is shown in Figure 2 below. Firstly, a XML file that defines the distribution of uncertain parameters should be established as UQ Repository. Sampling plugin will then generate samples according to the UQ Repository and then distribute them into building and weather module for further process. After the processing, the EnergyPlus built in the simulation engine module will run the IDF file and generate the results for final processing. 200 runs were performed for our analysis since no obvious change of results was observed if we further increased the number of runs of uncertainty analysis.

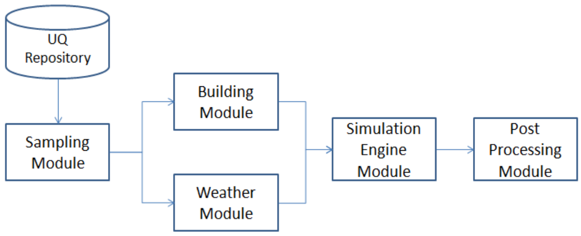

Figure 2. GURA workflow

3.3.7 Thermal Comfort Criteria

The argument for which thermal comfort criteria should be applied for hybrid ventilation building exists for a long period of time. Nowadays, in the European standard (EN 15251 [20]), the adaptive model could be applied for the hybrid ventilation building when the building is natural ventilation mode as long as (1) the building has operable window (2) no clothing protocol is forced. On the other hand, in US standard, the hybrid ventilation building is classified as air conditioned building since it has air conditioned presented. Thus, the graphical zone method, which is based on Fanger's PMV/PPD model [21], should be applied. However, recently, there is an increasing argument that the adaptive model is more suitable for thermal comfort evaluation of hybrid ventilation building compared to the PMV/PPD method. Thus, in our analysis, the adaptive model from ASHRAE 55 is applied for evaluation of thermal comfort of hybrid ventilation building. As shown in Figure 3 below, the thermal comfort zone (80% satisfactory) is determined by mean outdoor temperature for 15 consecutive days.

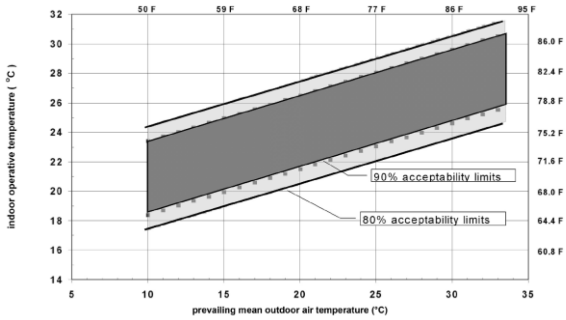

Figure 3. Adaptive Thermal Comfort Model

3.3.8 Building Control Strategy

As to control of the building, rule based control is used in our analysis for hybrid ventilation operation. It is the most widely used control methods for hybrid ventilation control due to its simplicity of implementation and easiness of design. In the rule based control strategy, the window openings or louver openings of a building are usually determined by the outdoor air temperature and wind speed.

In our analysis, for all the climates, the windows for the whole building were set to open when the outdoor temperature is between 18℃ and 24℃ based on the adaptive thermal comfort model mentioned above. Since the operative temperature for a building (especially for the second floor of our baseline building with roof exposure to the sun) could usually be several Celsius higher than the air temperature, this is a very reasonable range. No humidity limit was applied since the adaptive thermal comfort model has already taken it into account. The window is set to be off when the outdoor local wind speed is larger than 10 m/s.

4 Discussion and Result

After applying the uncertainty quantified for our analysis, both the results of potential energy saving and airflow volume increase in natural ventilation hours in four different representative cities that have most hybrid ventilation potential were presented below. Meanwhile, during natural ventilation hours for all cities, the thermally uncomfortable time are all within the 3% limits out of office hours.

As an example, Figure 4 below showed the result for Atlanta, which include the histogram of energy saving percentage and opening hour percentage (out of total office hour). For climate of Atlanta (3A mixed-humid), the energy saving is approximately 17% and has the standard deviation of 4.1%. Also, the windows could be opened for 12% of office hour throughout the year. Similarly, Figure 5 to 7 showed the results for Los Angeles (3B Coast), San Francisco (3C Marine) and Seattle (4C Marine). Overall, Table 3 summarized these results, in which the average and standard deviation for all the outputs were listed.

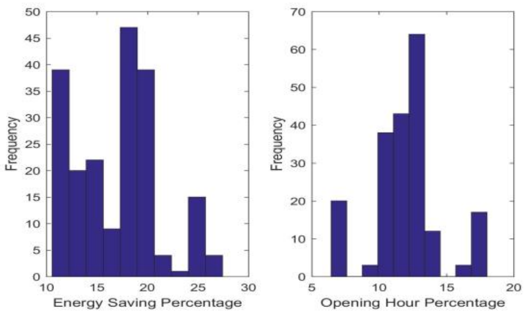

Figure 4. Atlanta result

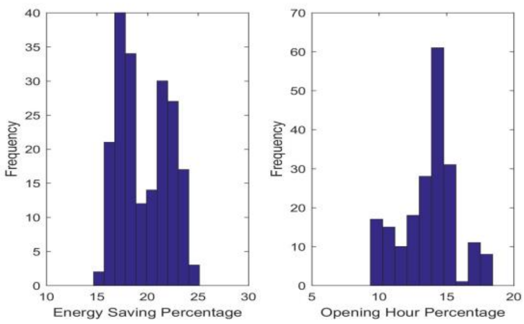

Figure 5. Seattle result

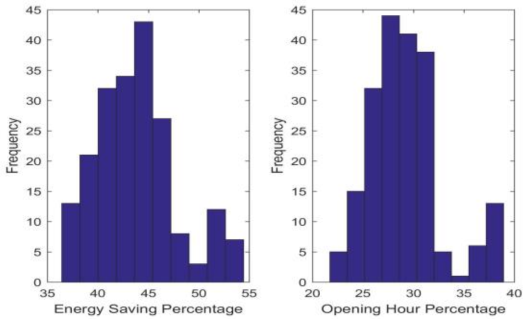

Figure 6. San Francisco result

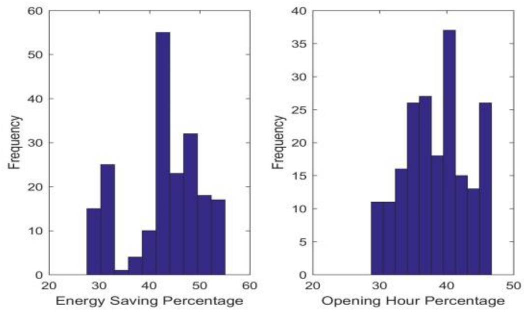

Figure 7. Los Angeles result

Table 3. Summary of Hybrid Potential Investigation Result Using Rule Based Control

City	Energy Saving		Window Opening Hour	
	Mean	Std	Mean	Std
Atlanta	17%	4.1%	12%	2.5%
Seattle	19.7%	2.5%	13.7%	2.1%
San Francisco	43.8%	4%	29%	3.6%
Los Angeles	42.9%	7.4%	38.5%	4.7%

5 Conclusion and Limitation

In this study, an uncertainty analysis was performed to evaluate the hybrid ventilation potential for possibly the most suitable climates for natural ventilation in US. Different levels of uncertainty were quantified first and then applied on our prototypical office building for simulation. The results showed that the energy saving on average could range from approximately 15% to 45% with an increase of airflow rate from 13 to 23 times. And the most suitable climates for hybrid ventilation are climates in Los Angeles (3B) and San Francisco (3C). As to limitation of the research, firstly, one important assumption of our analysis is that the occupants should operate the window in exactly the same way we have defined (open window as soon as the outdoor temperature is between 18℃ and 24℃). Thus, in the study, the uncertainties spring from occupant behavior are not accounted, which leads to the fact that our results tend to be more optimistic. With the advance of control technology, more complicated and effective control (e.g. model predictive control) could be applied for hybrid ventilation building as well. Consequently, in our future study, the uncertainties of occupants will further be quantified and more advance control technologies will be tested to improve our results of hybrid potential investigation.

6 Reference

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