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# Realizing natural ventilation potential through window control: The impact of occupant behavior

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## Abstract

As an increasingly popular green building technology, natural ventilation (NV) is an effective solution for better thermal comfort and lower HVAC system energy consumption. However, to achieve NV's full potential in practice, it is critical to control windows and HVAC systems. Three main types of control schemes are examined in this study: spontaneous occupant control, informed occupant control, and fully automatic control. Five representative climates, ranging from hot, temperate, to severely cold, are tested for the effectiveness of each control scheme. The results confirmed the superior performance of the fully automatic system, especially with the model predictive control algorithm, which demonstrates a cooling energy saving of 17%–80%, with zero discomfort degree hours. Neither the informed or spontaneous occupant controls are able to maintain the indoor temperature within the comfort range at all times. In particular, the informed occupant operation following the fixed-schedule four-times-daily signals shows the worst thermal control capacity and leads to 1500–4000 discomfort degree hours. In terms of energy performance, the informed occupant control, by following the heuristic control signals, shows the least energy savings and even indicates energy waste in some scenarios. Based on the study's results, it is recommended to either adopt the fully automatic natural ventilation control system to achieve maximum energy-saving potential or allow occupant autonomy for natural ventilation controls to achieve a lower budget for initial installation and maintenance cost.

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## 1. Introduction

Natural ventilation is an increasingly popular green-building technology that has been proven to be an effective solution to lower building cooling energy and to improve indoor air quality in various climates and types of building [1-3]. One of the most important factors for high-performance natural ventilation is the operation of windows. This issue is especially prominent in mixed-mode buildings. A variety of models have been established to predict window-operation behavior based on environmental and temporal factors, including season, time of the day, indoor and outdoor air temperature, indoor CO<sub>2</sub> concentration, as well as wind speed, humidity, noise level, rain, and outdoor PM<sub>2.5</sub> level [4-11]. Some correlations have been revealed either by logistic regression or simply the summary of the data. For example, the window-open periods are much longer in the summer than in the winter; people are more likely to open the window in the afternoon [12]; outdoor air temperature is positively correlated to the likelihood of window opening [13].

Manual control is an alluring option because of its simplicity and low maintenance. But when facing ever-changing external circumstances and dynamic internal occupants and activity, it may not be able to properly respond to the complicated and dynamic ambient environment due to inherent limitations. Since spontaneous occupant control generally shows sub-optimal performance in terms of energy savings and thermal comfort, advanced control strategies are proposed to better realize the natural ventilation potential in buildings. The most efficient window operation can be derived or calculated through a variety of methods, including the conventional rule-based heuristic control [14, 15], more advanced model predictive control (MPC) [16, 17], and newly developed control strategies that use artificial intelligence or machine-learning techniques, e.g. reinforcement learning control [18, 19].

In order to implement these window-control strategies based on the above-mentioned advanced methods, either informed occupant control or fully automated window systems are required in the application. With an informed occupant control system, the signal to either open or close the window will notify the corresponding occupant to take an action accordingly. With fully automated window systems, occupants still have the right to override the control, but will not have to take any action in daily operation.

Theoretically, the fully automated window-HAVC control system should be the best option to maximize natural-ventilation potential. However, in real-world projects, the extra initial cost and high maintenance needs of the automated system are major hurdles that stall wide adoption of the technology. In addition, there is no easily accessible comparison to show homeowners and developers how much of a performance boost they can expect from the advanced technology to justify their investment.

This research project aims to address the above issue and provide crucial information for decision making by answering questions such as how much energy can be saved by installing a fully automated window-HVAC control system, compared to spontaneous and informed occupant manual control.

## 2. Methodology

### 2.1 Model Description

A three-story building model was created to simulate the energy consumption and indoor thermal comfort in various testing cases. Only the results of south-facing room in the middle of the second floor were used to exclude the thermal effect from the roof, ground, and additional external wall exposure. The room has an area of 30m<sup>2</sup>, 30% window-to-wall ratio, 30% of operable glazing area, 5W/m<sup>2</sup> plug loads, and 2W/m<sup>2</sup>-100lux lighting energy. The room is assumed to be occupied 24h a day and constant HVAC system availability. The target comfortable temperature range is 20-25°C. The HVAC and control algorithms run on a 10-minute time step. Five Chinese cities from distinct climate zones: Harbin (Severe Cold), Beijing (Cold), Shanghai (Hot Summer Cold Winter), Guangzhou (Hot Summer Warm Winter), and Kunming (Mild) were studied. The construction complies with the Chinese Design Standard for Energy Efficiency of Public Buildings. The annual discomfort degree hour accumulates when the indoor temperature drops below 19°C (as cold degree hour) or rises above 26°C (as hot degree

hour). The cooling energy saving of the building is estimated with the physics-based building simulation developed on fundamental heat balance principles [18], which assumes a well-mixed indoor air temperature.

## 2.2 Control Strategies

### *Baseline Case*

In the baseline case, windows are kept closed all the time and the room is served by 100% mechanical ventilation. The HVAC system operates on the setpoints of the upper and lower limit of the comfort range. The cooling energy saving percentages of fully automated control, spontaneous control, and informed occupant control are compared against the cooling energy consumption of the baseline case.

#### 2.2.1 Fully Automated Control

##### *Heuristic Control*

The heuristic control strategy is based on the outdoor and indoor environment, such as air temperature, relative humidity, rain, wind, and the time of the day [4]. The room will switch to natural ventilation mode by opening the windows and turning off the AC when the specific indoor/outdoor requirements are met. In this study, the criterion for natural ventilation mode is when the indoor temperature higher than lower bound of the comfort range, the outdoor temperature higher than 18°C and lower than upper bound of the comfort range, and dew point lower than 17°C for the sake of humidity control. Whenever the windows are opened, the mechanical cooling system will be temporarily turned off. If any of the criteria are not met, the windows will be closed, and the HVAC system will be reactivated.

##### *Model Predictive Control*

Model predictive Control optimizes the operation of natural ventilation by simulating the system and choosing the best action based on the exhaustive testing scenarios ([open window, turn on AC], [open window, turn off AC], [close window, turn on AC], [close window, turn off AC]) run in parallel. The best action at each time step balances both the short-term and long-term thermal comfort and energy consumption by simulating on a multiple-step time horizon. In this case study, thermal comfort is given higher priority than energy consumption. If multiple actions all lead to a comfortable indoor temperature, the action that results in minimum energy consumption will be taken.

#### 2.2.2 Spontaneous Control

##### *Driven by Thermal Comfort*

Haldi and Robinson [20] developed a series of logistic models for the prediction of actions on windows based on seven years of measurements. Among these models including univariate and multivariate models with transformed or untransformed variables, the model with outside and inside air temperature has the highest statistical significance, and is the best one that fits the data. To ensure the applicability, extreme conditions are excluded when outside dry bulb temperature is below 10°C or above 30°C [21, 22], and the windows will be closed despite of the logistic regression results. In addition, the thermal comfort driven control is only valid 7am-11pm daily, excludes bedtime when occupants are considered irresponsive.

#### 2.2.3 Informed Occupant Control

Since occupants may not be able to predict the optimal window control schedules to achieve energy saving and thermal comfort, the use of signals notifying occupants when and how to take an action became a viable way to operate mixed-mode ventilation in buildings with manually controlled windows.

### *Fixed Operation Schedule*

In this scenario, occupants will check the signals at the four fixed points of time every day, namely 8am-9am (morning), 12pm-1pm (noon), 5pm-6pm (evening), and 10pm-11pm (night), to follow the signals and take an action accordingly. For the rest of the time in a day, the occupant will simply ignore the signals.

### *Stochastic Occupant Response*

In this scenario, occupants will either follow a signal or ignore it with a certain probability, during 8am-11pm wake time. There will be no further operation in the night during 11pm-8am. This study explores three cases, in which the occupants are assumed 80%, 50%, and 20% of chance to take an action accordingly, and ignore the signals rest of the time.

## **3. Results and Discussion**

### *3.1 Automatic Control*

#### *Cooling Energy Saving*

The fully automated system with either heuristic control and MPC shows significant cooling energy saving compared to the baseline case in which natural ventilation is not adopted. In all five cities, MPC leads to superior performance with 5%-17% more energy saving compared to the heuristic control. Kunming, the city located in the temperate climate zone shows the highest cooling energy saving of 66% with heuristic control and 80% with MPC. Harbin, the city located in the severe cold climate zone shows a high energy saving of 38% with heuristic control and 50% with MPC. Beijing (in cold climate zone) and Shanghai (in the hot-summer-cold-winter zone) show moderate cooling energy saving of 22% and 13% with heuristic control, and 27% and 31% with MPC. Guangzhou, the city located in the hot-summer-warm-winter climate zone shows a 10% of cooling energy saving by heuristic control and 17% of the saving by MPC.

#### *Discomfort Degree Hour*

The indoor temperature is perfectly maintained in the fully automated control cases, therefore zero discomfort degree hour is found in each city, either by heuristic control or MPC.

### *3.2 Spontaneous Control*

#### *Cooling Energy Saving*

The spontaneous control shows inferior energy performance compared with fully automated cases, illustrated in Fig. 1. It leads to [17.9%, 17.5%, 18.6%, 17.2%, 15.7%] less energy saving compared to MPC case, and [5.9%, 12.4%, 1.3%, 9.8%, 1.6%] less compared to the heuristic control. The energy performance of spontaneous control is particularly unsatisfactory in Guangzhou where 0% energy saving is observed.

#### *Discomfort Degree Hour*

Unlike the perfectly maintained indoor air temperature in fully automated cases, the spontaneous control results in a significant amount of discomfort degree hours, as shown in Fig.1. The hot degree hours when the indoor air temperature is above 26°C are [199, 362, 519, 417, 19] for Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively. The cold degree hours when indoor air temperature is below 19°C are [643, 767, 1121, 1077, 1158] for the cities in that order.

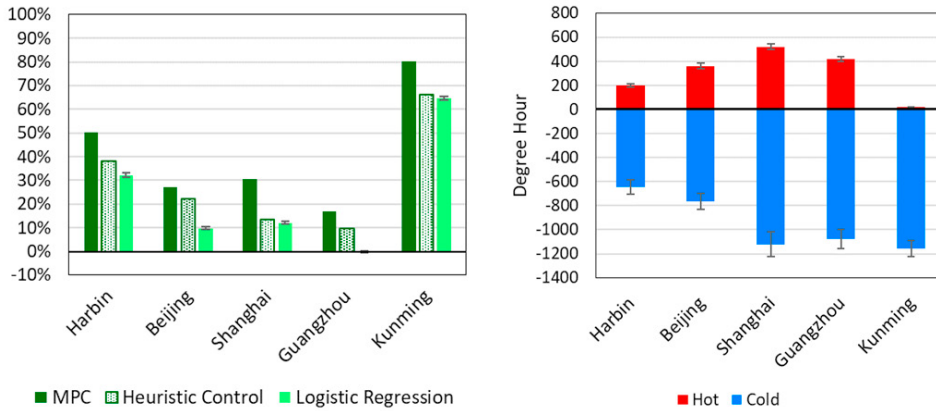


Fig. 1. Cooling energy saving (left) and discomfort degree hour (right) of spontaneous control

### 3.3 Informed Occupant Control – Scheduled

#### Cooling Energy Saving

Compared to fully automated cases, the four-times-daily operation following the heuristic control or MPC signals shows a dramatic reduction in cooling energy saving, as shown in Fig.2. The fixed schedule operation following the MPC signal leads to [15%, 19%, 13%, 15%, 11%] reduction in energy saving compared to its fully automated counterpart. The fixed schedule operation following the heuristic control signal leads to [10%, 12%, 13%, 12%, 18%] reduction in energy saving compared to its fully automated counterpart. Specifically, the four-times-daily operation following the heuristic control signal results in almost none cooling energy saving in Shanghai, and even higher energy consumption in Guangzhou compared to the non-NV baseline case.

#### Discomfort Degree Hour

Due to its poor performance in indoor air temperature control, both fixed schedule cases (the heuristic control and MPC) lead to considerable amount of discomfort degree hours, especially hot degree hours, in all five cities, as shown in Fig.2. For MPC signal case, there are more than 1000 hot degree hours in Harbin, around 2000 hot degree hours in Beijing, Shanghai, and Kunming, and more than 3000 hot degree hours in Guangzhou. For the heuristic control signal case, Harbin has more than 1000 hot degree hours, Beijing and Kunming have around 2000 hot degree hours, Shanghai has more than 3000 hot degree hours, and Guangzhou has more than 4000 hot degree hours.

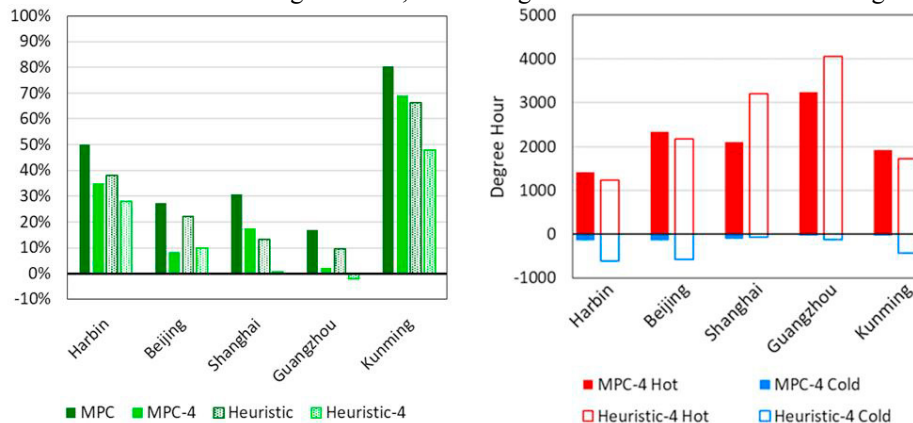


Fig. 2. Cooling energy saving (left) and discomfort degree hour (right) of informed occupant control with fixed schedule

### 3.4 Informed Occupant Control – Stochastic

#### Cooling Energy Saving

The energy saving performance of the stochastic occupant response control decreases with the diminishing probability of following the signal, in all five cities, as shown in Fig.3. It is noticed that all stochastic cases following the heuristic control signal in Guangzhou result in more energy consumption than the non-NV case. The same applies to Shanghai 20% case.

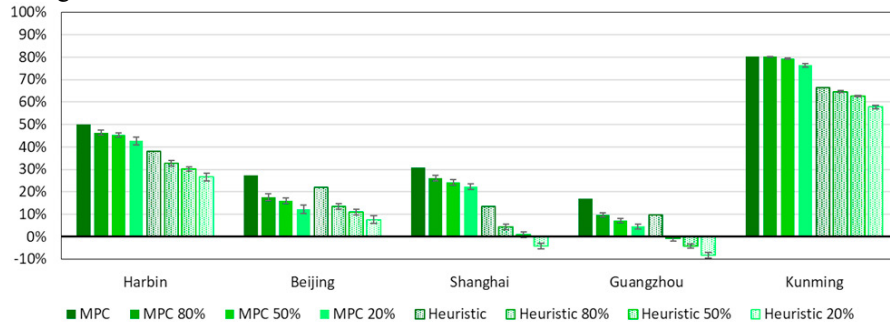


Fig. 3. Cooling energy saving of informed occupant control with stochastic response

#### Discomfort Degree Hour

The suboptimal performance of stochastic occupant response cases leads to significant amount of discomfort degree hours, especially hot degree hours in Shanghai and Guangzhou, as shown in Fig.4. It should be noticed that in all five cities with a range of 20% to 80% chance to follow the signal, the total discomfort degree hours are substantially less than the case of four-times-daily fixed-schedule control cases.

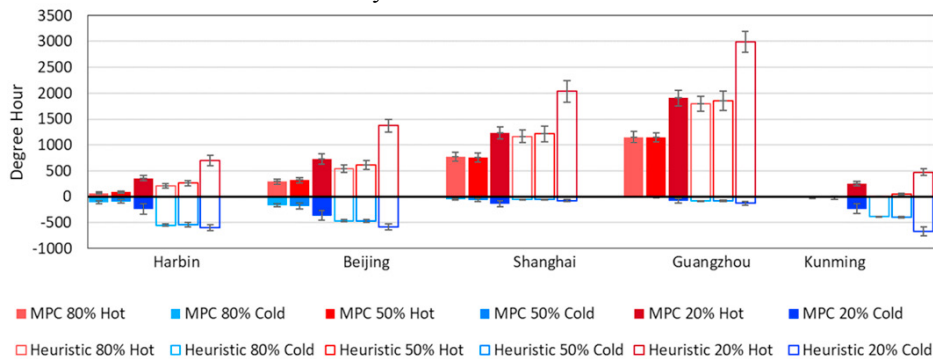


Fig. 4. Discomfort degree hour of informed occupant control with stochastic response

## 4. Conclusion

This study confirms the superior performance of the fully automatic natural ventilation control system, especially by MPC. Nevertheless, the informed occupant manual controls instructed by the signals fail to show significant improvement compared to the spontaneous occupant control. Therefore, it is recommended to choose between either fully automatic window-HVAC actuation system equipped with a computational backend for MPC, or to enable full-autonomy of spontaneous occupant control driven by thermal comfort and the desire for the fresh air. The results from the study have a potential to serve as a valuable reference for homeowners and developers when making the decision on NV system selection, by taking into consideration the annual energy saving and occupant satisfaction.

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