Achieving natural ventilation potential in practice: Control schemes and levels of automation

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HIGHLIGHTS

- Increasing levels of automation in natural ventilation control were analyzed.
- Fully automatic window/HVAC control system with MPC showed the best performance.
- Informed occupant control showed no significant improvement compared with spontaneous control.
- Improper NV control can introduce greater energy consumption and excessive discomfort.
- The selection of NV control system depends largely on the climate.

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ABSTRACT

A major challenge to fully achieve the natural ventilation (NV) potential in green buildings is the control and coordination of windows and the HVAC system. Three main types of control schemes with increasing levels of automation were examined in this study: spontaneous occupant control driven by thermal comfort, informed occupant manual control that follows instructional signals, and the fully automatic window/HVAC control system governed by either rule-based heuristic control criteria or a computational backend for model predictive control (MPC). Energy saving performance, indoor thermal comfort, and frequency of operation were used as metrics to evaluate various control schemes. We assessed the effectiveness of these control schemes using five representative climates in China that range from hot to severely cold. Our results demonstrated the advantage of fully automatic system, especially integrated with MPC, which showed energy savings of 17–80% with zero discomfort degree hours. In contrast with MPC, the fully automatic system with heuristic control showed 10–66% energy savings and the same discomfort degree hours. Neither the informed nor the spontaneous occupant control cases studied were able to maintain the indoor air temperature within the comfort range at all times. The informed occupant control in particular resulted in thousands of discomfort degree hours in the worst cases. The spontaneous occupant control showed moderate to no energy savings, whereas the informed occupant control introduced excessive energy usage in certain cases. Overall, the fully automatic NV control system exhibited the best energy saving performance and occupant satisfaction among studied control schemes despite of the additional initial investment. It is particularly true in climates where NV control has a considerable impact on building energy performance and employing improper NV control can cause energy waste and excessive thermal discomfort. In the selection of natural ventilation control system, our analysis suggests that developers and building owners should not only consider the initial system investment and maintenance cost, but also take into account the annual energy savings and occupant satisfaction to fully realize natural ventilation potential.

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1. Introduction

Green buildings aim to improve energy efficiency, reduce reliance on fossil fuels, and provide a pleasant and healthy indoor environment for greater occupant satisfaction and productivity. Natural ventilation (NV) is an increasingly popular green building technology that is an effective solution to lower building cooling energy and to improve indoor air quality in various climates and building types [1–11]. However, the successful implementation of natural ventilation relies on several crucial factors, such as the immediate urban context [12–15], building type [16], floor plan [17], ambient air quality [18–22], and noise level [23,24]. Some of these factors need to be considered at the design stage, and others are addressed during daily operations. One of the most important factors for high-performance natural ventilation is the operation of windows [25–27]. This issue is especially crucial in mixed-mode buildings that combines natural and mechanical ventilation [28]. Various levels of automation can be found in practice, which range from the most common spontaneous manual control to very advanced fully automatic systems.

Spontaneous window-operation behavior is an ongoing research topic [29]. Stemming from long-term surveys and monitoring data of significant samples of occupants around the world, some shared behavior patterns have been revealed. For example, the window-open periods were much longer in the summer than in the winter [30,31], the window-operation frequency was higher in non-heating seasons [32], and people were more likely to open windows in the afternoon [33]. Statistical models, such as logistic regression, have been established to predict window-operation behavior based on environmental and temporal factors that include season, time of the day, indoor and outdoor air temperature, indoor CO₂ concentration, wind speed, humidity, noise level, rain, and outdoor PM2.5 concentration [34–41].

Although manual control is an alluring option because of its simplicity and low maintenance, it may not respond properly to complicated and dynamic external circumstances nor internal activities of occupants due to its inherent limitations. Because spontaneous occupant control generally shows sub-optimal performance in energy savings and thermal comfort, advanced control strategies have been 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, which include conventional rule-based heuristic control [42,43], more advanced model predictive control (MPC) [44,45], and newly developed control strategies that use artificial intelligence or machine-learning techniques [46–48] (e.g., reinforcement learning control [49]). Implementing these advanced window-control strategies requires either informed occupant control or fully automatic window systems. With an informed occupant control system, the signal to either open or close windows notifies the corresponding occupant to take an appropriate action [50,51]. With fully automatic window systems, occupants still have the right to override the control, but they will not need to take any action during daily operation. Theoretically, the fully automatic window/HVAC control system should be the best option to maximize NV potential. However, in real-world projects, the extra initial cost and high maintenance of the system are major hurdles that stall wide adoption of the technology. In addition, there is no easily accessible comparison to show building owners and developers how much of a performance boost they can expect from the advanced technology to justify their investment.

This paper addresses these issues and provides crucial information for decision-making by quantifying how much energy can be saved by installing a fully automatic window/HVAC control system, compared with either a spontaneous occupant control or an informed occupant control. This study investigated, in a variety of climates in China, the effectiveness of different window/HVAC control strategies: (1) fully automatic window and HVAC systems that were controlled and actuated by a backend system with either rule-based heuristic control or model predictive control algorithms, (2) spontaneous occupant control that was driven by thermal discomfort, and (3) informed occupant control, in which occupants were informed by a signal to operate the windows. The signals were sent by a system that was monitoring weather and indoor activity constantly to calculate the optimal window condition. The modeled behavior mimicked realistic human behavior; specifically, characteristics including limited frequency of operation, delay, and negligence, were modeled through (A) a four-times-daily fixed schedule, and (B) a stochastic process in which the occupant had probabilities either to obey or to neglect the signal. The results demonstrated the sensitivity of energy consumption and indoor thermal comfort to various control schemes.

2. Methodology

A three-story building model was created to simulate energy consumption and indoor thermal comfort in various test cases. Only the results for a south-facing room in the middle of the second floor were used so that the thermal effect from the roof, ground, and additional external wall exposure could be excluded. The single occupancy room as a single thermal zone had an area of 30 m², 30% window-to-wall ratio, 30% operable glazing area, 5 W/m² plug loads, and 2 W/m²-100 lx lighting energy. The room was assumed to be occupied 24 h a day with constant HVAC system availability. The target comfortable temperature range was 20–25 °C [52–57]. The HVAC and control algorithms ran on a 10-min time step. A co-simulation of building energy using EnergyPlus and control systems using self-developed Python program was implemented on the platform of Building Controls Virtual Test Bed (BCVTB) developed by the Lawrence Berkeley National Laboratory [58]. The MPC control was realized through a data-driven approach using Scikit-learn library in Python. Five Chinese cities from distinct climate zones were selected for the study: Harbin (Severe Cold), Beijing (Cold), Shanghai (Hot Summer, Cold Winter), Guangzhou (Hot Summer, Warm Winter), and Kunming (Temperate) (Fig. 1). The weather data used in this study is the hourly Chinese Standard Weather Data (CSWD) developed by China Meteorological Bureau and Tsinghua University [59]. The construction complied with the Chinese Design Standard for Energy Efficiency of Public Buildings (Table 1). The annual discomfort degree hours accumulated when the indoor temperature dropped below 19 °C (as cold degree hours) or rose above 26 °C (as hot degree hours).

The cooling energy saving of the building was estimated with EnergyPlus developed by U.S. Department of Energy [49,60] (Eqs. (1)–(3)), which assumed a well-mixed indoor air temperature.

\[ \rho C_v V \frac{dT}{dt} = Q_{in} + Q_{load} + Q_c + Q_{AC} + Q_{NV} \]  
(1)

where \( \rho \) is the air density, \( C_v \) is the specific heat of air, \( V \) is the volume of the zone, \( T \) is indoor air temperature, \( Q_{in} \) is the heat transfer rate through the building envelope, \( Q_{load} \) is the internal heat gain rate from people and equipment, \( Q_c \) is the heat gain rate from solar radiation, \( Q_{AC} \) is the cooling rate from the HVAC system, and \( Q_{NV} \) is the heat gain rate through natural ventilation, which was derived from

\[ Q_{NV} = \rho C_v \hat{V}_{NV} (T_{out} - T_{in}) \]  
(2)

where \( T_{out} \) is outside air temperature, \( T_{in} \) is indoor air temperature, and \( \hat{V}_{NV} \) is natural ventilation rate which is a function of wind-driven and buoyancy-driven effects

\[ \hat{V}_{NV} = \sqrt{(V_{wind})^2 + (V_{buoy})^2} \]  
(3)

where \( V_{wind} \) is proportional to local wind speed, and \( V_{buoy} \) is positively correlated to indoor/outdoor temperature differences.

2.1. Control strategies

2.1.1. Baseline case

In the baseline case, windows were kept closed all the time and the
room was served by 100% mechanical ventilation. The HVAC system operated on setpoints per the upper and lower limits of the comfort range. The percentage of cooling energy saving of the fully automatic control, the spontaneous occupant control, and the informed occupant control cases were calculated via comparison with the cooling energy consumption of the baseline case. In all studied cases, the heating system ran independently, and it was triggered automatically whenever the indoor air temperature dropped below the lower bound of the comfort range.

2.1.2. Fully automatic control

2.1.2.1. Heuristic control. The heuristic control strategy is based on the outdoor and indoor environment, such as air temperature, relative humidity, rain, wind, and time of day [2,49]. The room ventilation switched to natural ventilation mode by opening the window and turning off the HVAC system when the specific indoor/outdoor requirements were met. In this study, the natural ventilation mode was activated when the indoor air temperature was higher than 20 °C, the outdoor air temperature was higher than 18 °C and was lower than 25 °C, and the dew point temperature was lower than 17 °C for the sake of humidity control. Whenever the windows were opened, the mechanical ventilation and air conditioning system turned off temporarily. If any of the criteria were not met, the windows were closed, and the HVAC system was reactivated.

2.1.2.2. Model predictive control. Model Predictive Control (MPC) optimizes the operation of natural ventilation by finding the best immediate action in a series of exhaustive testing scenarios ([open window, turn on HVAC], [open window, turn off HVAC], [close window, turn on HVAC], [close window, turn off HVAC]) through parallel simulations. The best action at each time step balanced both the short-term and long-term thermal comfort with energy consumption by simulating the physics model of the dynamic system on a multiple-step time horizon from the current state (Eqs. (4)–(6)). In this case study, thermal comfort was given higher priority than energy consumption. If multiple actions all led to a comfortable indoor temperature, the action that resulted in minimum energy consumption was preferred.

$$\hat{a}_t = \arg\min_{a \in A} J_t$$

given

$$J_t = \sum_{i=1}^{n} \omega_d \max(T_{in,i} - T_{air}, 0) T_{in,i} - T_{air} + \sum_{i=1}^{n} \omega_c C_i$$

and

$$T_{in,t+1} = f(T_{in,t}, \hat{a}_t, \Phi_t)$$

where $\hat{a}_t$ is the action selected for timestep $t$, $A$ is the set of all possible actions, $J_t$ is the cost function to be minimized, $\omega_d$ is the weighting coefficient penalizing discomfort, $\omega_c$ is the weighting coefficient for energy consumption, $T_{in,i}$ is the indoor air temperature at time $t$, $T_{air}$ and $T_{low}$ are upper and lower threshold of the comfort range, respectively, $C_i$ is the operation status of HVAC at time $t$, and $\Phi_t$ is the comprehensive building and weather conditions at time $t$.

2.1.3. Spontaneous control

2.1.3.1. Driven by thermal comfort. Haldi and Robinson [61] developed a series of logistic models for the prediction of actions on windows based on seven years of measurements of 14 south-facing cellular rooms. Among these models, which included univariate and multivariate models with transformed or untransformed variables, the model with outdoor air temperature $T_{out}$ and indoor air temperature $T_{in}$ had the highest statistical significance and was the model that best fit the data (Eq. (5)),

$$\logit(p) = \log\left(\frac{p}{1-p}\right) = a + b_1 T_{out} + b_2 T_{in}$$

where $p$ is the probability for using the natural ventilation, $a = 1.459$, $b_1 = 0.14477$, $b_2 = -0.1814$, $T_{out}$ is outdoor air temperature, and $T_{in}$ is the indoor air temperature in °C.

To ensure the applicability of the above derived equation, extreme climate zones were categorized by the number of days with daily average temperature below 5 °C or above 25 °C.

Table 1

<table>
<thead>
<tr>
<th>Climate zone</th>
<th>$T_{daily} \leq 5 , ^oC$</th>
<th>$T_{daily} \geq 25 , ^oC$</th>
<th>Roof</th>
<th>Wall</th>
<th>Window</th>
<th>Window SHGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe cold</td>
<td>$\geq145$</td>
<td>--</td>
<td>0.25</td>
<td>0.35</td>
<td>1.76</td>
<td>0.68</td>
</tr>
<tr>
<td>Cold</td>
<td>90-145</td>
<td>--</td>
<td>0.39</td>
<td>0.46</td>
<td>1.77</td>
<td>0.37</td>
</tr>
<tr>
<td>Cold winter hot summer</td>
<td>0-90</td>
<td>40-110</td>
<td>0.39</td>
<td>0.54</td>
<td>2.3</td>
<td>0.32</td>
</tr>
<tr>
<td>Warm winter hot summer</td>
<td>--</td>
<td>100-200</td>
<td>0.44</td>
<td>0.72</td>
<td>2.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Temperate</td>
<td>0-90</td>
<td>--</td>
<td>0.44</td>
<td>0.72</td>
<td>2.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>
conditions were excluded when outside dry bulb air temperature was \(< 10^\circ\text{C} \) or \(> 30^\circ\text{C} \) [32,63,63] (in these conditions the windows were closed regardless of the \(p\) value). In addition, the spontaneous control was only valid 7 am–11 pm daily, which excluded bedtime when occupants were considered irresponsible.

2.1.4. Informed occupant control

Because occupants may not be able to predict the optimal window control schedules to achieve maximum energy saving and thermal comfort, the use of signals that notify occupants when and how to take an action has been proposed as a viable way to operate mixed-mode ventilation in buildings with manually controlled windows. Those signals can be sent from either a central or distributed control hubs running computations (e.g. MPC) or simply monitoring the environment (e.g. heuristic control).

2.1.4.1. Fixed operation schedule. In this scenario, occupants checked the signals at four fixed times every day, namely 8 am–9 am (morning), 12 pm–1 pm (noon), 5 pm–6 pm (evening), and 10 pm–11 pm (night), and took an action suggested by the signals during that hour. For the rest of the time in a day, occupants simply ignored the signals.

2.1.4.2. Stochastic occupant response. In this scenario, occupants followed signals with a certain probability during 8 am–11 pm wake time. There was no further operation during 11 pm–8 am. Three scenarios were explored in this study in which we assumed that the occupants had probabilities of 80%, 50%, and 20% of taking an appropriate action, and ignored the signals otherwise.

3. Results

We measured the duration of natural ventilation throughout the year, the total daily operation frequency, and the point of time when actions were taken. The performance of studied control strategies was quantified through the cumulative distribution of the indoor air temperature, the total annual discomfort degree hours (> \(26^\circ\text{C}\) or \(< 19^\circ\text{C}\)) and the cooling energy savings compared with the non-NV baseline case.

3.1. Automatic compared with spontaneous

The characteristics of natural ventilation, including NV duration and window operations, are analyzed in this section for fully automatic control cases (MPC and heuristic control) and spontaneous occupant control case. The statistics for the informed occupant control cases were either trivial or can be derived directly from the fully automatic control cases, therefore are not included here.

3.1.1. The duration of natural ventilation

The NV duration of fully automatic MPC and heuristic control, along with the spontaneous occupant control in the five studied cities are illustrated in Fig. 2. In the severe cold (Harbin) and cold (Beijing) climates, the opportunities for natural ventilation were prohibited in the winter under all three control strategies. In the summer of the cold-winter-hot-summer (Shanghai) and warm-winter-hot-summer (Guangzhou) climates, nearly zero NV was allowed by the heuristic control, while occasional NV was instructed by MPC depending on the weather of the day, and consistently substantial NV duration under spontaneous occupant control. The temperate climate (Kunming) showed a high rate of window opening during noon to capture the free cooling by allowing just an adequate amount of natural ventilation.

3.1.2. The frequency of system operation

The daily window/HVAC system operation frequency of MPC, heuristic control, and spontaneous control in the five studied cities are illustrated in Fig. 3. The occurrences of zero daily operation when the natural ventilation was prohibited by inclement weather (either too hot or too cold) are not shown in the figure. The total number of window operations (fully open or close) in five cities over the course of an entire year was 3394–6996 with MPC, 560–1636 with heuristic control, and 1380–2728 with spontaneous control.

Compared to the heuristic control and spontaneous control, MPC had a much higher frequency of window/HVAC control operations. The median daily operation frequencies were 18, 18, 20, and 19 for Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively, and the 80th percentile daily operation frequencies were 27, 25, 34, 33, and 28 for the same five cities in the corresponding order. Such high daily operating frequency implied a very low possibility for sufficiently functional manual control by occupants who need to follow the MPC signals.

In general, the observed frequencies of window/HVAC control operations that followed the heuristic control strategy demanded a fairly light duty on the mechanical control system compared to MPC. Excluding the zero-operation days, more than one-third of the time only twice-daily operations were expected in all five cities. The median daily operation frequencies were 3, 3, 4, 2 and 4 for Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively, and the 80th percentile daily operation frequencies were 6, 6, 9, 7, and 12 for the same five cities in the corresponding order.

In the spontaneous control cases, the frequency of daily window operation was \(\leq 14\) for all five cities. The median daily operation frequencies were 8, 6, 8, 8, and 8 for Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively. The 80th percentile daily operation frequency was 10 for all five cities. These frequencies were consistent with reasonable human behavior patterns.

3.1.3. The daily distribution of system operation

Fig. 4 illustrates on radar charts the time of the day when window/HVAC operations took actions. A day is divided into six blocks of four-hour-duration periods: morning (6 am–10 am), noon (10 am–2 pm), afternoon (2 pm–6 pm), evening (6 pm–10 pm), night (10 pm–2 am), and late night (2 am–6 am). Higher rates of occurrence are plotted towards the edge, while the center of a radar chart represents zero operations. Under MPC, most of the window/HVAC control actions were taken during the daytime, and almost none were taken during the sleeping time from 10 pm to 6 am. This was advantageous for minimal occupant disturbance, maintenance, and troubleshooting. The spontaneous occupant control showed dominant patterns of higher rates of window opening in the early morning and window closing at night, which agreed with routine habits of occupants. Compared to MPC and spontaneous control, the heuristic control was more heterogeneous across the five cities, and with substantial occurrence of operations during the night. For the cities in colder climates that employed NV mostly during the warmer season, Harbin and Beijing demonstrated a higher rate of window opening in the early morning and a higher rate of window closing at night, mainly due to the diurnal temperature swings to take advantage of warmer daytime air and to avoid chilling night air. For cities in warmer climates, a higher occurrence of operations occurred during the late night to benefit from the breezy cool air.

For the city in a hot climate where NV in the winter was possible, Guangzhou showed a high rate of window opening during noon to capture the warmth from the winter sun. For the city in a temperate climate,
Fig. 2. The daily duration of natural ventilation throughout the year in the five cities.
Kunming, the particularly high operation rate during late night was due to the slight fluctuation in outside air temperature around the threshold set in the heuristic control, which led to repetitive opening and closing. This is one of the major weaknesses of rule-based control schemes with hard-cut criteria.

3.1.4. 24 h excerpt
To better understand the difference among three control schemes, the 24 h period of May 27th in Kunming was selected for closer observation. The outside air temperature was 15–21 °C during this period, the indoor air temperature was within the comfort range of 20–25 °C under both MPC and heuristic control, and the indoor air temperature dropped below 20 °C for 5 h in the morning under the spontaneous control (Fig. 5). Specifically, MPC instructed pulse NV (10 min) to occur at different times during the day, which maintained indoor thermal comfort effectively. The heuristic control instructed that mechanical cooling occur around noon to keep the indoor air temperature below the upper bound of the comfort range, while outside air temperature was cool but below the 18 °C threshold imposed by the heuristic control criteria. During the night, due to prolonged NV periods in the afternoon and evening, indoor air temperature dropped below the lower bound of the comfort range, which triggered the heating system. For the spontaneous control, the long morning NV duration resulted in cold indoor air temperature that triggered the heating system, which ran for 5 h concurrently with opened windows.

The limitation of the heuristic control in this study was that it had no ability to consider future weather conditions and predicted indoor thermal conditions. For example, the threshold of 18 °C to allow natural ventilation aimed to prevent over-cooling by extended periods of NV when it was cold outside, but at the same time it lost some NV opportunities. Although the heuristic control can be improved to cover such scenarios with more sophisticated criteria, it almost certainly will lead to more complicated case-by-case algorithms that are difficult to manage and to debug. For the spontaneous control, the concurrent heating and natural ventilation are commonly seen in the real world, as reported by Laurent et al. [23].

3.2. Automatic, informed, and spontaneous control

The indoor air temperature, thermal discomfort degree hours, and energy saving performance (compared with Non-NV baseline) of fully automatic control cases, spontaneous occupant control case, and informed occupant control cases are analyzed in this section.

3.2.1. Indoor air temperature

The cumulative distribution of indoor air temperature under all 12 control schemes is shown in Fig. 6. A steep slope of the curve indicates a high occurrence of the indoor air temperature within that corresponding temperature range on the x axis, and a flat slope of the curve indicates a low occurrence of the indoor air temperature within that range on the x axis. The target temperature range of 20–25 °C is shaded in gray, and the one-degree leeway (i.e., 19–20 °C and 25–26 °C) is shown in a lighter shade of gray. The portion of curves that is outside of the gray area implies uncomfortable thermal conditions.

For the Non-NV baseline case, the plot shows that most of the time the indoor air temperature was around the lower bound (20 °C) and higher bound (25 °C) of the target range, with very steep curves around these two ends and a flat section in-between. For the fully automatic cases, the indoor temperature was well maintained within the comfort range by both MPC and heuristic control in all five cities, which resulted in zero discomfort degree hours.

For the spontaneous control, indoor air temperature fluctuated. A significant amount of discomfort time was observed in all five cities. Occurrences of hot temperature were seen in Harbin, Beijing, Shanghai, and Guangzhou with indoor temperatures that exceeded the upper limit of the comfort range but generally below 28 °C. Cold temperature incidences prevailed in all five cities with indoor air temperatures below the lower limit of the comfort range, and there were several times when indoor temperature dropped to 15 °C.

The fixed-schedule daily operations that followed the signals from either MPC or the heuristic control were insufficient to maintain an acceptable indoor temperature. Specifically, indoor air temperature was above 26 °C for 10–30% of the time in the five cities. Even worse, excessive heat incidences when indoor air temperature rose above 30 °C were also seen in all five cities (i.e., the curves did not reach 100% cumulative density at 30 °C).

The stochastic occupant response cases also resulted in poorly maintained indoor air temperatures with undesirable hot and cold occurrences. In general, for both heuristic control signal and MPC signal cases, the ability to maintain a desirable indoor temperature decreased with the diminishing probability of occupants’ compliance with the signals. Therefore, cases when the occupants only had a 20% probability of following a system control signal led to the worst performance, which resulted in a significant number of hot conditions and occasional excessive heat occurrences above 30 °C.

3.2.2. Discomfort degree hours

Total discomfort degree hours of each city under various control schemes are illustrated in Fig. 7. As already mentioned, indoor air temperature was maintained perfectly in the Non-NV and two fully automatic control cases (MPC and heuristic) and, therefore, no discomfort degree hours were seen in any of the cities.

Unlike the perfectly maintained indoor temperature in fully automatic cases, spontaneous control resulted in a significant number of
discomfort degree hours. The number of hot degree hours when the indoor temperature was above 26 °C were 199, 362, 519, 417, and 19 for Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively. The cold degree hours when indoor temperature was below 19 °C were 643, 767, 1121, 1077, and 1158 for the cities in that same order.

Similarly, due to its poor performance in thermal control, both fixed schedule cases (the heuristic control signals and MPC signals) led to a considerable number of discomfort degree hours, especially hot degree hours, in all five cities. For the MPC signal case, Harbin had > 1000 hot degree hours, Beijing, Shanghai, and Kunming had approximately 2000 hot degree hours, and Guangzhou had > 3000 hot degree hours. For the heuristic control signal case, Harbin had > 1000 hot degree hours,
Beijing and Kunming had approximately 2000 hot degree hours, Shanghai had > 3000 hot degree hours, and Guangzhou had > 4000 hot degree hours.

For the stochastic occupant response cases, performance decreased with the diminishing probability of the occupants following the signals and taking actions in both MPC and heuristic signal cases; this was especially true when a dramatic plunge in performance of thermal comfort and energy saving occurred when the chance of compliance dropped from 50% to 20%. Setting a threshold of 1200 discomfort degree hours, the cases that failed to meet the standard were R_Heu_20% in Harbin; R_Heu_20% in Beijing; R_MPC_20%, R_Heu_50%, and R_Heu_20% in Shanghai; R_MPC_50%, R_MPC_20%, R_Heu_80%, R_Heu_50%, and R_Heu_20% in Guangzhou. The discomfort degree hours are below 1200 for all stochastic cases in Kunming.

Fig. 8 illustrates the annual percentage of total discomfort time in each city under twelve control schemes. Except for Non-NV and fully automatic cases (both MPC and heuristic control) where no discomfort time was found, Guangzhou showed the highest percentage of discomfort time (9–29%), followed by Shanghai (6–21%), and Beijing (3–20%). Harbin and Kunming showed the lowest percentage of discomfort time, specifically 1–12% and 0.1–14%, respectively.

3.2.3. Energy performance

Fig. 9 summarizes the cooling energy savings of each city under all studied control schemes. Compared against the Non-NV baseline, the fully automatic system with either MPC or heuristic control showed significant energy savings. In all five cities, MPC demonstrates superior performance with 5–17% more energy savings compared with the heuristic control. Kunming, the city located in a temperate climate showed the highest cooling energy savings of 66% with heuristic control and 80% with MPC. Harbin, the city located in a severe cold climate, showed a high energy saving of 38% with heuristic control and 50% with MPC. Beijing (cold climate), and Shanghai (hot-summer-cold-winter) showed a moderate cooling energy savings of 22% and 13% with heuristic control, and 27% and 31% with MPC, respectively. Guangzhou, the city located in the hot-summer-warm-winter climate showed a 10% cooling energy saving by heuristic control and 17% with MPC.

The spontaneous control showed inferior energy performance compared with fully automatic cases. It resulted in 32%, 10%, 12%, 0%, and 65% energy saving in Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively. The energy performance of spontaneous control was particularly unsatisfactory in Guangzhou, where there was no energy saved compared to the Non-NV baseline case.

Compared to fully automatic cases, the four-time daily operations that followed the heuristic control or MPC signals showed a dramatic decrease in cooling energy savings. The fixed schedule operation that followed the MPC signal resulted in 15%, 19%, 13%, 15%, and 11% drop of energy savings in Harbin, Beijing, Shanghai, Guangzhou, and Kunming, respectively, compared with its fully automatic counterpart. The fixed schedule operation that followed the heuristic control signal resulted in 10%, 12%, 13%, 12%, and 18% drop of energy saving compared to its fully automatic counterpart for the same corresponding cities. Specifically, the four-time daily operation that followed the heuristic control signal resulted in almost no cooling energy saving in Shanghai and even higher energy consumption in Guangzhou compared to the Non-NV baseline case.

The energy saving performance of the stochastic occupant response control decreased with the diminishing probability of following the signals in all five cities. All stochastic cases (R_Heu_80%, R_Heu_50%, and R_Heu_20%) that followed the heuristic control signal in Guangzhou resulted in more energy consumption than the Non-NV case. The same was true for Shanghai R_Heu_20% case.

4. Discussion and conclusion

The fully automatic control with mechanical window actuators and coordinated window/HVAC control system demonstrated substantial cooling energy savings and perfectly maintained the indoor temperature in all five studied cities. Specifically, the control system instructed by the heuristic criteria resulted in energy savings of 10–66%. The control system instructed by the MPC algorithms showed higher energy savings of 17–80%. The indoor air temperature was within the comfort range year-round. No thermal discomfort degree hours were found in any of the studied cities with the fully automatic control systems.

The total number of window operations annually was between 3000 and 7000 for MPC cases and between 500 and 1700 for the heuristic control cases. The most common daily operation frequencies were around 20 in MPC cases, and twice-daily for the heuristic cases. The operation time was mostly during the day in the MPC cases and during the morning, evening, and late night in the heuristic control cases. Consequently, MPC could only be realized by an automatic control...
Fig. 6. The cumulative distribution of indoor air temperature under all 12 control schemes in the five cities.
system due to its high operation frequency. Similarly, the heuristic control also provided little opportunity for full manual control due to the inconvenient time of day when operations were necessary.

The spontaneous occupant control that was driven by thermal comfort was not able to maintain the indoor temperature within the comfort range at all times. Both hot and cold occurrences were seen in all five cities. Spontaneous occupant control showed lower cooling energy savings by 1–12% and 16–18% compared with the fully automated heuristic control cases and MPC cases, respectively.

Two types of informed occupant control were explored in this study. For the fixed-schedule daily operations, both cases that followed the heuristic control signals or MPC signals showed unsatisfactory results in indoor thermal comfort and energy performance. Hot conditions, especially when indoor air temperature rose above 30 °C, were not rare in all five cities regardless of the type of signals sent, which resulted in a large number of discomfort degree hours. In addition, the fixed-schedule operation also led to 10–19% lower energy saving compared to the fully automatic cases. In Shanghai and Guangzhou, it resulted in near zero energy savings, or even higher energy consumptions than Non-NV baseline cases. For the stochastic occupant response cases, performance decreased with the diminishing probability of following the signals in both the heuristic control and MPC cases. In particular, there was a dramatic decrease in performance of thermal comfort and energy saving when the chance of compliance dropped from 50% to 20%. Overall, the MPC signal cases showed better performance in thermal comfort and energy saving compared with the heuristic cases. The higher energy consumptions compared to Non-NV baseline were seen in all three stochastic scenarios following heuristic signals in Guangzhou, and the case of 20% chance following the heuristic signals in Shanghai.

Although the stochastic occupant control with a high probability of occupant compliance showed better performance than the fixed-schedule control, 80% and 50% stochastic control that followed the MPC signals still resulted in a very high frequency of daily operations that were required of the occupants. Both forms of informed occupant control, either with the fixed schedule or with a probability of proper response, inevitably incurred a considerable amount of discomfort degree hours. In real-world practice, this could bring increased frustration and distrust towards the system by the occupants, which could lead to a growing reluctance to respond and, eventually, to ignore the signals altogether and to convert to 100% HVAC mode instead.

This study has demonstrated that the fully automatic natural ventilation control system integrated with MPC displayed significant energy savings of 17–80% with zero discomfort degree hours. In comparison, the fully automatic system with conventional heuristic control...
showed 10–66% energy savings. Neither the informed nor spontaneous occupant control cases studied were able to maintain the indoor air temperature within the comfort range at all times. The informed occupant control failed to show significant improvement over the spontaneous occupant control, aside from the practical concern that occupants’ conformance to signals might not sustain in the longer term. Although natural ventilation has great potential to reduce building energy consumption and improve indoor thermal comfort, improper operation of window and HVAC system may instead cause energy waste and excessive discomfort. Therefore, NV control is crucial in buildings with mixed-mode ventilation, particularly in climates with intermittent natural ventilation opportunities. In the selection of NV control system, our analysis suggests that developers and building owners should not only consider the initial system investment and maintenance cost, but also take into account the annual energy savings and occupant satisfaction to fully realize natural ventilation potential.

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