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Smart control of windows for intermittent ventilation in public housing in Hong Kong based on deep neural network models

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Climate change has led to an increase in the frequency and intensity of heatwaves, making Hong Kong particularly hot during summer months. As a result, residents in Hong Kong's public housing buildings heavily rely on air conditioning, leading to poor ventilation when used for extended periods. To achieve proper ventilation, people often resort to intermittent ventilation, opening windows for short periods to allow fresh air to circulate. However, there is currently no specific guideline or approach tailored for public housing in Hong Kong. To address this issue, the study proposed a smart control strategy for windows to achieve effective intermittent ventilation with the shortest window opening duration for public housing in Hong Kong. First, deep neural network (DNN) models were developed to predict the ventilation rate for each unit of a public housing building in Hong Kong, with the database obtained from computational fluid dynamics (CFD) and multi-zone airflow models. Based on the trained DNN models, a smart window control strategy was proposed to minimize the window opening period for intermittent ventilation. The results show that, for the 12 studied cases, on average, the proposed algorithm minimized the window opening duration for intermittent ventilation to 9.5 min, which was 68% shorter than the 30-min guideline, while maintaining the same intermittent ventilation effectiveness. The proposed smart control strategy for intermittent ventilation can minimize the window opening period so that thermal discomfort and exposure to heat could be minimized, especially for the elderly, in public housing during hot seasons in Hong Kong.

KEYWORDS

intermittent ventilation, smart window control, deep neural network model, public housing, thermal comfort

1 Introduction

Hong Kong is among the most crowded cities in the world. With a resident population of over 7,400,000 in 2021, the average population density in Hong Kong was 6,740 persons per km^2 (Census and Statistics Department, 2022). Notably, among the population in Hong Kong, 45% of people live in public housing units (Hong Kong Housing Authority, 2021). According to the Chief Executive's 2022 Policy Address (Chief Executive's Office, 2022), 158,000 more public housing units will be constructed over the next 5 years. This number is 50% greater than in the previous 5-year period. Hence, the population in public housing will remain considerably large for the foreseeable future. According to the State of World Population Report 2023 from the United Nations Population Fund, Hong Kong has the lowest fertility rate in the world (United Nations Population Fund, 2023). With a longer life expectancy (Census and Statistics Department, 2022), Hong Kong is now facing the inevitability of an aging population. Therefore, it is important to improve the indoor environmental quality in public housing, since elderly people stay at home for most of their time (Chau et al., 2002).

Climate change has led to an increase in the frequency and intensity of heatwaves (Mitchell et al., 2016), making Hong Kong particularly hot during summer months. As a result, residents in Hong Kong's residential buildings heavily rely on air conditioning to stay cool. However, a lot of home air conditioners currently in use do not provide fresh air, leading to poor ventilation when used for extended periods. This lack of proper ventilation can cause a buildup of indoor air pollutants, which poses significant health risks to the occupants (Godish and Spengler, 1996). Therefore, it is crucial to address the ventilation issues in public housing in Hong Kong, especially given the heavy reliance on air conditioners due to the hot climate. Improving ventilation to ensure a supply of fresh air can help mitigate the adverse health effects associated with prolonged air conditioner use. Several studies have estimated the ventilation rates in various residential housing types in Hong Kong. For instance, Ai et al. (2016a) measured the ventilation rate in an air-conditioned bedroom of a typical residential building. Cheung and Jim (2019) assessed the ventilation rates in eight substandard residential units. Lai et al. (2020) performed blower-door tests to determine the air change rates and air permeability in ten high-rise and low-rise residential apartments. These studies have provided valuable insights into the ventilation rates in residential buildings in Hong Kong. However, in the hot climate, keeping the windows open is not practical. Therefore, further research is needed to explore operational strategies for effective ventilation.

To achieve proper ventilation, people often resort to intermittent ventilation, opening windows for short periods to allow fresh air to circulate. This approach has been particularly recommended during the COVID-19 pandemic to reduce the risk of virus transmission. The Chinese Health Commission advised that household rooms should open windows for a minimum of 30 min twice daily (Lai et al., 2020). Some studies in the literature have focused on the effectiveness of intermittent ventilation (Su et al., 2023; Ai et al., 2016b; Melikov et al., 2020); however, there is currently no specific guideline or approach tailored for public housing in Hong Kong. If the window opening time is too short, the ventilation may be insufficient to improve indoor air quality. Note that residents in public housing in Hong Kong typically switch off their unitary air conditioners when the windows are open to reduce energy expenses. Therefore, if the windows are left open for too long, thermal comfort is compromised, and the increased exposure to heat can pose significant health risks, especially for the elderly. Therefore, it is crucial to develop advanced and optimized approaches for intermittent ventilation that balance air quality and thermal comfort, ensuring the wellbeing of residents in Hong Kong's public housing.

To address this issue, the study proposed a smart control strategy for windows to achieve effective intermittent ventilation with the shortest window opening duration for public housing in Hong Kong. First, deep neural network (DNN) models were developed to predict the ventilation rate for each unit of a public housing building in Hong Kong. The database for training the DNN models was obtained using computational fluid dynamics (CFD) and multi-zone airflow network models validated by field measurements. Based on the trained DNN models, a smart window control strategy was proposed to minimize the window opening period for intermittent ventilation when an air conditioner needed to be used to combat heat in public housing in Hong Kong. The aim was to minimize the window opening period so that thermal discomfort and exposure to heat could be minimized, especially for the elderly. Case studies were conducted to demonstrate the effectiveness of the proposed smart window control strategy for intermittent ventilation in public housing in Hong Kong.

2 Methods

2.1 Development of the DNN models

This study first developed DNN models to predict the ventilation rate for each unit of a public housing building in Hong Kong. The inputs included wind conditions and the structural parameters of the housing. The database for training was established through numerical simulations. These numerical models were validated using field measurements.

2.1.1 Database establishment for training

2.1.1.1 Site selection

This research concentrated on public housing structures utilizing the modular flat design implemented by the Hong Kong Housing Authority. Figure 1 illustrates the floor plans of the four modular flat types: 1-Person/2-Person (1/2P), 2-Person/3-Person (2/3P), 1-Bedroom Flat (1B), and 2-Bedroom Flat (2B). The living room, bedrooms, kitchen, and bathroom are equipped with casement windows. Each flat type includes two exhaust fans, one in the kitchen and another in the bathroom. To create a database for model training, this study chose Cheung Tai House, depicted in Figure 2, as the target building due to its representativeness. Situated in the Cheung Sha Wan district, a densely populated area in downtown Hong Kong with a building density of 0.3, it reflects the general urban environment. Cheung Tai House, a public housing building with a Y-shaped design, exemplifies the design shape predominantly used by the housing authority with the modular flat design concept.

2.1.1.2 Numerical simulations

A database of ventilation rates was developed using numerical simulations for Cheung Tai House. Initially, wind pressures on the target building were determined using computational fluid dynamics (CFD) simulations. The realizable k-ε model was employed for turbulence modeling (Franke et al., 2011; Blocken et al., 2012). The simulations were conducted using the commercial software ANSYS Fluent. The general form of the turbulence model can be expressed by Equation 1:

$$\rho\frac{\partial\overline{\phi}}{\partial t}+\rho\overline{u}_i\frac{\partial\overline{\phi}}{\partial x_i}-\frac{\partial}{\partial x_i}\left[\Gamma_{\phi,eff}\frac{\partial\overline{\phi}}{\partial x_i}\right]=S_\phi \tag{1}$$

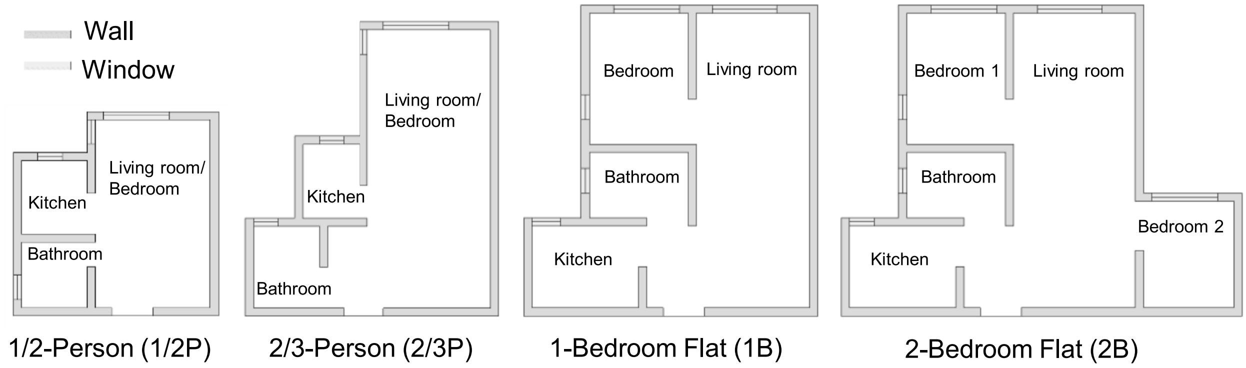

FIGURE 1
Floor plans of the modular flat design.

FIGURE 2
City view of Cheung Tai House (in the red rectangular) and its surrounding region retrieved from Google Maps.

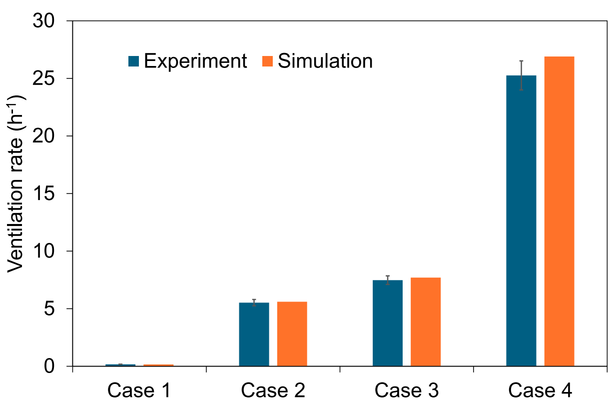

FIGURE 3
Comparison of ventilation rates predicted by the numerical models and the on-site measurement data in Cheung Tai House.

where ρ is the air density (kg/m^3), t is the time (s), $\overline{u_i}$ is the air velocity (m/s), x_i are the coordinates (m), ϕ represents turbulence parameters, $\Gamma_{\phi,eff}$ is the effective diffusion coefficient, and S_ϕ is the source term. A detailed description of the model can be found in the Fluent manual (Dai and Chen, 2022).

Based on our earlier studies (Brown and Solvason, 1962), the computational domain was defined as extending 3.5 times the height (H) of the tallest nearby building, using a 3D digital model from the Hong Kong Lands Department. To prevent artificial acceleration of airflow over the structure, the domain was expanded to 5H at the lateral and upper boundaries (Franke et al., 2011). Wind and turbulence intensity profiles, sourced from the Planning Department's database, were used to establish the inlet boundary conditions. Wind speed and direction data were obtained from the Hong Kong Observatory. Following the guidelines of Franke et al. (2011), symmetry was applied to the top and side boundaries to ensure parallel flow, while the outlet was designated as a pressure outlet. The study assumed isothermal conditions throughout. A total of 23 CFD simulation scenarios, each representing different wind speeds and directions, were analyzed to encompass the majority of wind conditions. Intermediate cases were computed using a trilinear interpolation method. A grid-independence test revealed that a resolution of 8.0 million cells was adequately fine. The standard wall function was applied, with y+ values ranging between 30 and 200. The SIMPLE algorithm was employed to couple the pressure and velocity equations. Second-order discretization was utilized for the pressure, momentum, turbulence kinetic energy, and turbulent dissipation rate equations.

Ventilation rates for all residential units under various ventilation settings were determined using a multi-zone airflow network model, with wind pressures derived from CFD simulations serving as inputs. Airflow between adjacent zones was represented as flow paths with different flow elements. The airflow rate through a leakage was calculated using the effective air leakage area as specified in the ASHRAE Handbook. For windows influenced by the stack effect, the airflow rate was calculated using the two-way model (Brown and Solvason, 1962). Following the recommendations of Kwok et al. (2017) and validated by Dai et al. (2024), the indoor air temperature was assumed to be 2°C higher than the outdoor air temperature under natural ventilation conditions. The airflow rate through exhausts in the bathroom and kitchen was assumed to be constant. Internal doors were considered fully open and modeled as orifice elements. Based on a survey of residents in

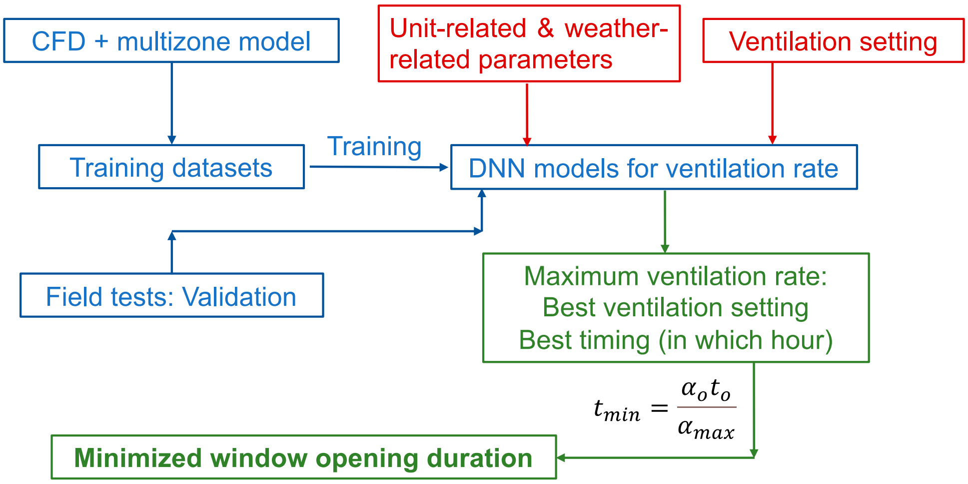

FIGURE 4
Flowchart of the smart window control algorithm for intermittent ventilation when air conditioner needed to be used for combat heat in the public housing in Hong Kong.

TABLE 1 Case setup.

Case no.	Room no.	Annual-average ventilation rate	Wind speed on the test day
1	1	High (6.35 ACH)	High (Average: 13.8 m/s)
2	1	High (6.35 ACH)	Medium (Average: 4.0 m/s)
3	1	High (6.35 ACH)	Low (Average: 2.1 m/s)
4	1	High (6.35 ACH)	Large variation (0.2–25.8 m/s)
5	2	Medium (5.91 ACH)	High (Average: 13.8 m/s)
6	2	Medium (5.91 ACH)	Medium (Average: 4.0 m/s)
7	2	Medium (5.91 ACH)	Low (Average: 2.1 m/s)
8	2	Medium (5.91 ACH)	Large variation (0.2–25.8 m/s)
9	3	Low (5.13 ACH)	High (Average: 13.8 m/s)
10	3	Low (5.13 ACH)	Medium (Average: 4.0 m/s)
11	3	Low (5.13 ACH)	Low (Average: 2.1 m/s)
12	3	Low (5.13 ACH)	Large variation (0.2–25.8 m/s)

public housing estates in Hong Kong, the average window opening angle was found to be 22°, leading to a discharge coefficient of 0.26 (Yang et al., 2010). The multi-zone airflow network simulations were conducted using the CONTAM software, allowing for the calculation of ventilation rates for each residential unit under specific conditions using Equation 2:

$$\alpha_{i,j,k} = \frac{3600 Q_{i,j,k}}{V_i} \tag{2}$$

where $\alpha_{i,j,k}$ is the ventilation rate (h^{-1}) in the residential unit i under the wind condition j with the ventilation setting k, $Q_{i,j,k}$ is the total airflow rate (m^3/s) in the residential unit i under the wind condition j with the ventilation setting k, and V_i is the volume of the residential unit i (m^3). Wind pressures obtained from CFD simulations were used as inputs for the respective flow elements in the multi-zone airflow network model. By varying the operational states (open/closed or on/off) of the living room and bedroom windows, bathroom window, kitchen window, bathroom exhaust, and kitchen exhaust, a total of 32 ($2^5 = 32$) different ventilation settings were analyzed.

To verify the accuracy of the numerical models, on-site measurements were taken at Cheung Tai House to determine

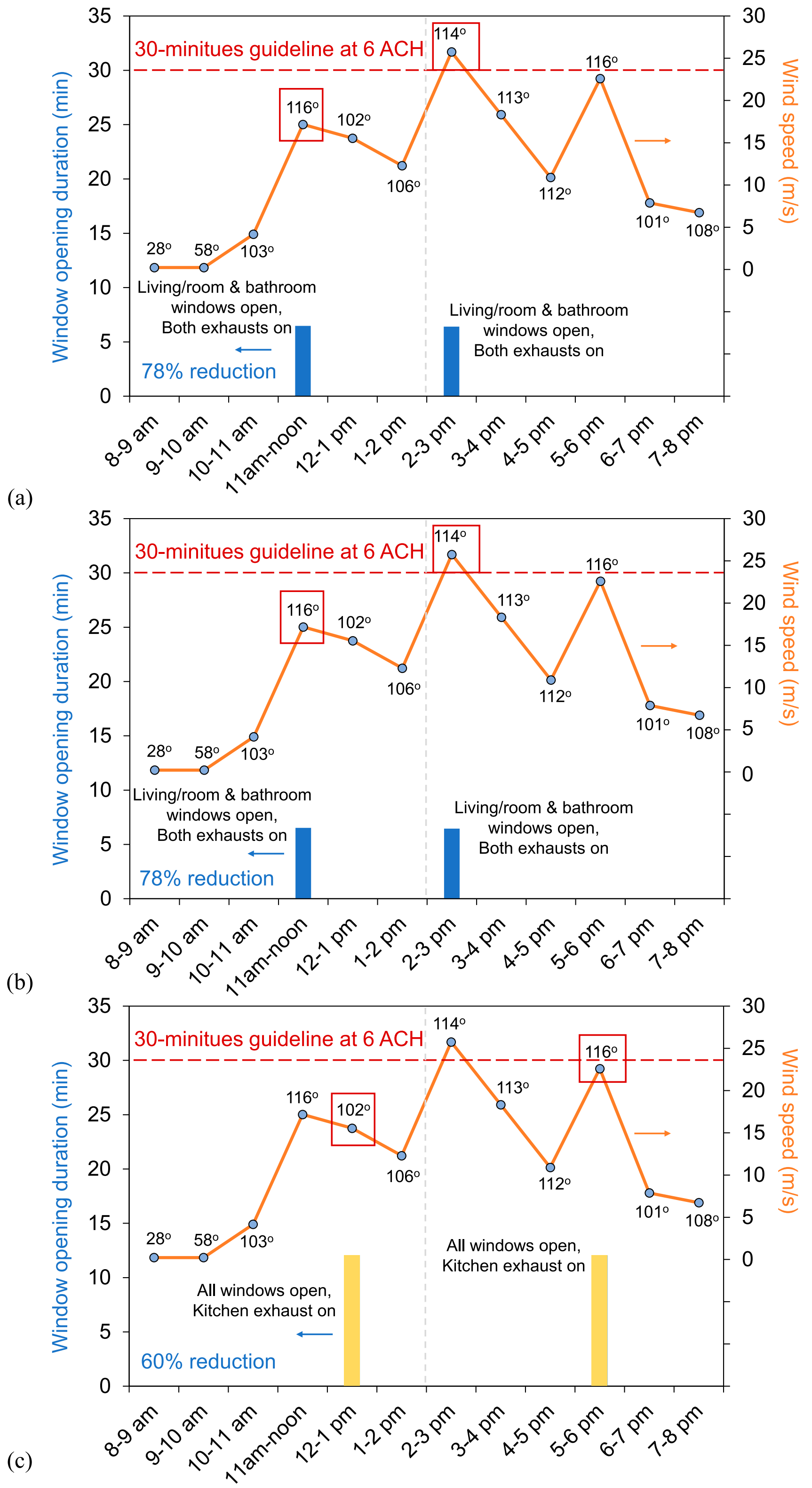

FIGURE 6
Optimized ventilation setting and time as well as the minimized window opening duration for intermittent ventilation (equivalent to 30 min at 6 ACH) calculated using the proposed algorithm for **(a)** Room 1 (high annual-averaged ventilation rate), **(b)** Room 2 (medium annual-averaged ventilation rate), and **(c)** Room 3 (low annual-averaged ventilation rate) on the typical days with large wind speed variation. The two bars are the minimized window opening duration for intermittent ventilation. The point line is the wind speed (secondary vertical axis). The numbers represent wind directions.

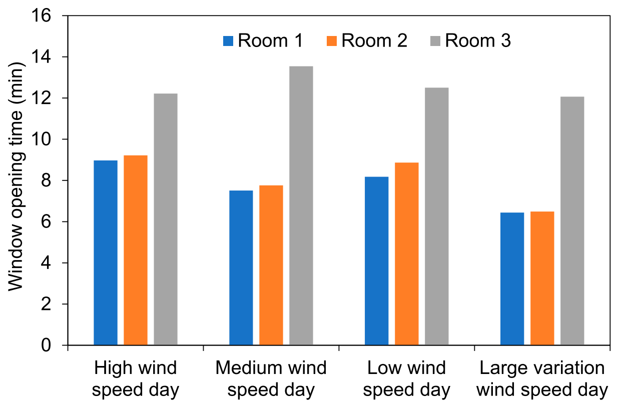

FIGURE 7
Minimized window opening time for intermittent ventilation (equivalent to 30 min at 6 ACH) calculated using the proposed algorithm for Rooms 1, 2, and 3 (high, medium, and low annual-averaged ventilation rate) on the four typical days.

ventilation rates under various conditions using the CO_2 decay method. During the measurement, CO_2 was released in the tested unit, and its concentrations over time were recorded by a CO_2 sensor (Testo 440-CO_2 probe; Testo SE & Co. KGaA, Germany) with an accuracy of 3%. The ventilation rate in the tested unit under the given ventilation setting can be determined by fitting the data to the following Equation 3:

$$C_i(t) = C_o + [C_i(0) - C_0]e^{-\frac{\alpha}{3600}t} \tag{3}$$

where $C_i(t)$ is the indoor CO_2 concentration (ppm), $C_i(0)$ is the initial indoor CO_2 concentration (ppm), C_o is the outdoor CO_2 concentration (ppm), and α is the ventilation rate (h^{-1}). Four distinct scenarios were evaluated. In Case 1, natural ventilation was assessed with the kitchen window open. Case 2 involved mixed ventilation with both the bathroom and kitchen windows open and their exhaust fans activated. Case 3 examined mixed ventilation with the living room/bedroom and kitchen windows open, along with the bathroom exhaust fan on. Case 4 included mixed ventilation with the living room/bedroom and kitchen windows open and both the bathroom and kitchen exhaust fans running. Figure 3 presents a comparison between the ventilation rates predicted by the numerical models and the actual measurements. The calculated rates closely matched the measured data, showing an average relative error of 4.3%. Consequently, these numerical models were utilized to simulate ventilation for all residential units in Cheung Tai House.

2.1.2 Training of the DNN models

With 596 residential units in Cheung Tai House analyzed under 23 different wind conditions and 32 distinct ventilation settings, the database comprised a total of 438,656 ventilation rate datasets. This research developed 32 DNN models, each corresponding to one of the 32 ventilation settings. Each DNN model included 17 input features representing key influencing factors. Three of these input features pertained to wind conditions (wind speed, wind direction, and the power-law exponent of the wind profile), data that can be readily obtained from the Hong Kong Observatory and the Site Wind Availability System by the Hong Kong Planning Department. In the context of Hong Kong's public housing modular flat design, window number and size are standardized for specific room types. Consequently, 14 input features related to the residential units were considered, including floor height, room volume, sizes of the six windows, and window orientation relative to wind direction for these windows. These inputs are accessible via the GeoInfo Map and the 3D Digital Map from the Hong Kong Lands Department. For simplicity in data formatting, angular features were converted to their sine and cosine values. The DNN models' output was the ventilation rate for each residential unit under the specified ventilation setting. The dataset of 438,656 entries was divided into training, validation, and testing datasets in a 70%, 20%, and 10% ratio, respectively. To ensure consistency and prevent scale mismatches, all input features were normalized by Equation 4:

$$\acute{x}_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{4}$$

where $\dot{x}_i$ is the normalized data point for the input features, x_i is the original data point for the input features, and x_{min} and x_{max} are the minimum and maximum values of the data for the input features.

The architecture of DNN was used because it is suitable for classification and regression. The DNN models were built using a 6-layer architecture with the following structure: 24 × 64 × 32 × 32 × 16 × 1. This included one input layer, four hidden layers, and one output layer. The architecture, including the number of layers and neurons per layer, was determined through iterative testing to achieve the best predictive performance. The hidden layers utilized the Rectified Linear Unit (ReLU) function as the activation function. The mean squared error (MSE) was employed as the loss function as shown in Equation 5:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(\tilde{Y}_i - Y_i)^2 \tag{5}$$

where n is the number of training samples, i is the ith sample in the datasets, $\tilde{Y}_i$ is the predicted value for the ith data point, and Y_i is the actual value of the ith data point. The Adam optimizer was employed for training the models, with the learning rate set at 0.001. The batch size was configured to 64, and the training was conducted over 2,000 epochs. To mitigate overfitting, an early stopping mechanism with a patience of 50 epochs was implemented.

2.2 Smart window control algorithm

The objective of the smart window control was to minimize the window opening period for intermittent ventilation when an air conditioner needed to be used to combat heat in public housing in Hong Kong. During the COVID-19 pandemic, the Chinese Health Commission advised that household rooms should open windows for a minimum of 30 min twice daily (Lai et al., 2020). According to previous research by Su et al. (2023), when the ventilation rate is greater than 6 ACH, intermittent ventilation for 30 min twice a day can provide satisfactory indoor air quality over the course of 12 h. Therefore, this study assumed that as long as intermittent ventilation can provide the total fresh air volume equivalent to 6 ACH for 30 min within 6 h, the strategy can provide satisfactory indoor air quality. For instance, if the ventilation rate can reach 12 ACH under certain wind conditions for a given residential unit, the residents can open the windows for only 15 min to receive sufficient intermittent ventilation. As a result, the occupants, especially the elderly, would be exposed to less heat during hot weather.

The ventilation rate would vary with different ventilation settings under different wind conditions. Therefore, we hypothesize that within a 6-h period, there would be an optimal time and ventilation setting for intermittent ventilation to achieve the maximum ventilation rate. Consequently, the duration needed for intermittent ventilation can be minimized in order to reduce the occupants' exposure to heat. The intermittent ventilation duration required to achieve a total fresh air volume equivalent to 6 ACH for 30 min can be calculated by

$$t_{min} = \frac{\alpha_o t_o}{\alpha_{max}} \tag{6}$$

where t_{min} is the minimized intermittent ventilation duration, α_{max} is the maximum ventilation rate that can be achieved within the 6 h, α_o is equal to 6 ACH, and t_o is equal to 30 min.

To identify the best time and ventilation setting for intermittent ventilation to achieve the maximum ventilation rate, the developed DNN models were used, as illustrated in Figure 4. Among the 17 inputs for the DNN models, 14 were parameters related to the unit structure. Therefore, for the target residential unit, these 14 inputs can be easily determined. The other three inputs were parameters related to wind conditions. According to the hourly wind condition information and forecasts provided by the Hong Kong Observatory, these three inputs can be obtained. Specifically, the ventilation rates under the 32 ventilation settings in each hour of the next 6 h can be predicted using the 32 DNN models. This results in a total of 192 (32 × 6) predicted ventilation rates. By comparison, the highest ventilation rate can be identified, along with its corresponding ventilation setting and time (i.e., the specific hour). The intermittent ventilation duration can then be calculated using Equation 6. Therefore, the best ventilation setting and time, as well as the minimized duration for intermittent ventilation, can be executed.

2.3 Case setup

To demonstrate the effectiveness of the proposed window control strategy for intermittent ventilation, this study selected three residential units with relatively high, medium, and low annual average ventilation rates for the 2B flat types, as the 2B units generally had relatively low ventilation rates due to their larger volume (Dai et al., 2024). Three typical days in Hong Kong with relatively high, medium, and low wind speeds, as well as another day with a large variation in wind speed, were selected to represent the influence of wind conditions. Note that typhoon days were excluded. The best ventilation settings and times, as well as the minimized duration for intermittent ventilation, were calculated using the algorithm described above. The effectiveness of the proposed window control strategy for intermittent ventilation in reducing the duration of heat exposure (air conditioner turned off and windows open) was then evaluated. The case setup is shown in Table 1.

3 Results

Figure 5 shows the optimized ventilation settings and times, as well as the minimized duration for intermittent ventilation calculated using the proposed algorithm for Room 2 on the four typical days. Room 2 had the medium annual-average ventilation rate, representing an average unit in Cheung Tai House in terms of natural ventilation. As a reference, the Chinese Health Commission advises that household rooms should open windows for a minimum of 30 min twice daily (Lai et al., 2020). Therefore, the aim of the developed algorithm was to minimize the window opening duration twice a day but equivalent to 30 min at 6 ACH (Su et al., 2023). The hourly wind speed and direction are shown in the figure. As shown in Figure 5a, on the high wind speed day, the algorithm determined that the living/bedroom and bathroom windows should be opened and both exhausts should be turned on for 9.2 min during 12–1 p.m., and the same operation for 9.2 min during 2–3 p.m. This window opening strategy was equivalent to 30 min at 6 ACH. The window opening duration was reduced by around 69% due to the higher ventilation rate predicted by the algorithm. Figures 5b, c show the results on the medium and low wind speed days, respectively. On the medium wind speed day, the algorithm determined that all the windows should be opened and both exhausts should be turned on during 9–10 a.m. and 5–6 p.m. The window opening time was 7.1 min and 8.4 min, respectively. On the low wind speed day, the algorithm determined that all the windows should be opened and both exhausts should be turned off for 9.3 min during 12–1 p.m. and 5–6 p.m., and the living/bedroom and bathroom windows should be opened and both exhausts should be turned on for 8.4 min during 7–8 p.m. Figure 5d shows the results on a day with large wind speed variation. With significant wind speed variation, the timing for opening windows may be more crucial if the aim is to shorten the window opening duration. The algorithm determined that the living/bedroom and bathroom windows should be opened and both exhausts should be turned on from 11 a.m. to noon and 2–3 p.m., respectively. The window opening durations were both 6.5 min, obviously shorter than that on the days with smaller wind speed variation. Interestingly, the ventilation setting of opening living/bedroom and bathroom windows and turning on both exhausts was the most favorable, mainly because it created least air resistance to the unit (Dai et al., 2024). Clearly, the proposed algorithm can significantly reduce the window opening duration compared with the 30-min guideline, while maintaining the same intermittent ventilation effectiveness. This may be attributed to the advantage that the proposed algorithm could always identify the best hourly wind condition in a day to maximize the natural ventilation rate. This would reduce thermal discomfort as well as exposure to heat for public housing residents, especially the elderly.

Figure 6 shows the optimized ventilation settings and times, as well as the minimized duration for intermittent ventilation, calculated using the proposed algorithm for the three rooms on a typical day with large wind speed variation. Room 1, Room 2, and Room 3 has high, medium, and low annual-averaged ventilation rates, respectively, representing a wide range of units in Cheung Tai House in terms of natural ventilation. For Room 1, which has a high annual-averaged ventilation rate, as shown in Figure 6a, the algorithm determined that the living/bedroom and bathroom

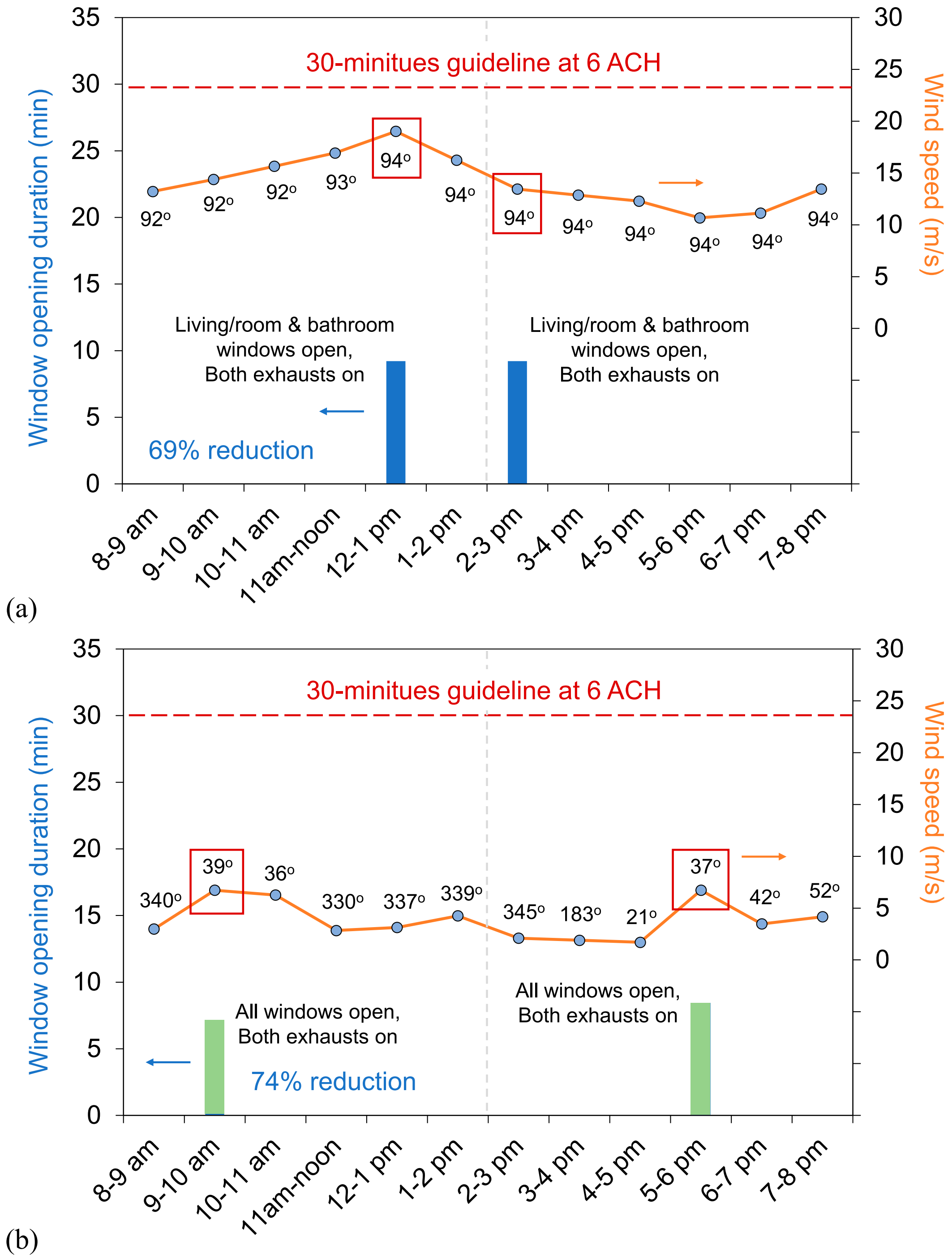

FIGURE 5
(Continued).

windows should be opened and both exhausts should be turned on for 6.5 min from 11 a.m. to noon and for 6.4 min from 2–3 p.m. Figure 6b is the same as Figure 5d. For Room 3, which has a low annual-averaged ventilation rate, as shown in Figure 6c, the algorithm determined that all the windows should be opened and the kitchen exhaust should be turned on for 12.1 min during 12–1 p.m. and 5–6 p.m., respectively. Clearly, the unit orientation and configuration significantly influenced the minimized window opening duration. Some units could have lower window opening durations than others because of their better orientation and configuration for natural ventilation. Again, the proposed algorithm can significantly reduce the window opening duration compared with the 30-min guideline, while maintaining the same intermittent ventilation effectiveness.

Figure 7 shows the minimized window opening duration for intermittent ventilation (equivalent to 30 min at 6 ACH) calculated

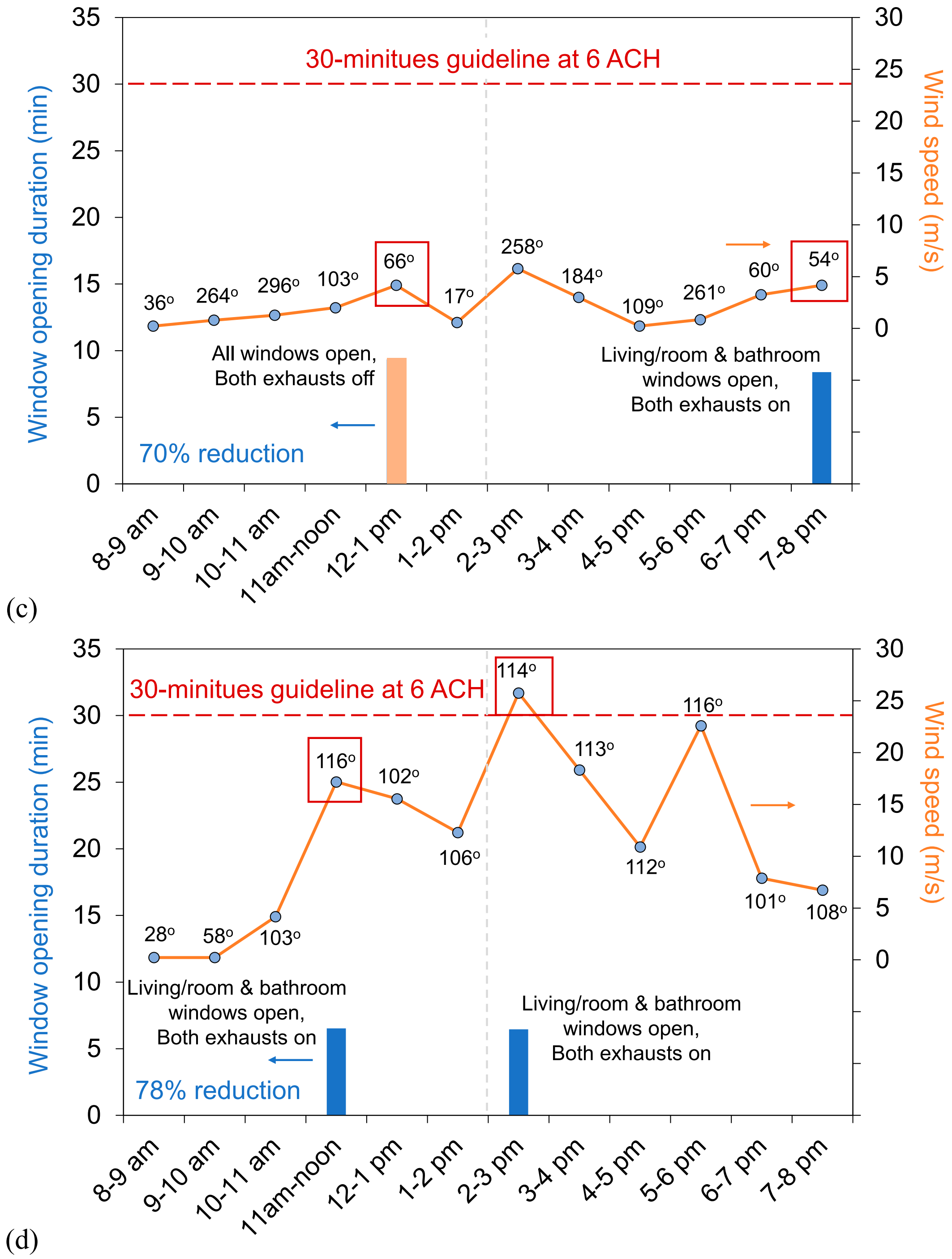

FIGURE 5
(Continued). Optimized ventilation setting and time as well as the minimized window opening duration for intermittent ventilation (equivalent to 30 min at 6 ACH) calculated using the proposed algorithm for Room 2 (medium annual-averaged ventilation rate) on the four typical days: **(a)** high wind speed, **(b)** medium wind speed, **(c)** low wind speed, and **(d)** large wind speed variation. The two bars are the minimized window opening duration for intermittent ventilation. The point line is the wind speed (secondary vertical axis). The numbers represent wind directions.

using the proposed algorithm for all three rooms on the four typical days, totaling 12 cases. Note that each result represents the average of the two window opening durations in a day. On average, the minimized window opening duration was 9.5 min, which was 68% shorter than the 30-min guideline. This reduction would benefit residents in public housing in Hong Kong in terms of thermal comfort and reduced risks of heat exposure during the hot summer.

4 Discussion

This study developed a method for minimizing the window opening duration for intermittent ventilation in public housing in Hong Kong. There are some limitations and prospects to consider. First, to promote intelligent control, the proposed algorithm can be integrated into an Internet of Things (IoT) system. For example, there are numerous window opening actuators available on the market for a few hundred Hong Kong dollars that can be connected to smartphones or cloud servers. A window opening actuator and a controller that can receive weather forecasts from the Hong Kong Observatory can be integrated with the proposed algorithm specified for each unit. With such a system, manual operation would not be needed, allowing residents to enjoy a smarter and more comfortable living environment. Second, this study did not consider other factors such as rainy or highly polluted days. In real applications, intermittent natural ventilation may also need to account for the influence of adverse weather conditions. Finally, this study used the Chinese Health Commission's 30-min guideline as a reference. However, the actual effectiveness of intermittent ventilation should be assessed by the removal of indoor air pollutants. More studies are needed to develop more accurate and locally specific references or guidelines for intermittent ventilation.

5 Conclusion

This study proposed a smart control strategy for windows to achieve effective intermittent ventilation with the shortest window opening duration for public housing in Hong Kong. First, DNN models were developed to predict the ventilation rate for each unit of a public housing building in Hong Kong, with the database obtained from CFD and multi-zone airflow models. Based on the trained DNN models, a smart window control strategy was proposed to minimize the window opening period for intermittent ventilation when an air conditioner needed to be used to combat heat in public housing in Hong Kong. Within the scope of this work, the following conclusions can be drawn.

1. For the 12 studied cases, on average, the proposed algorithm minimized the window opening duration for intermittent ventilation to 9.5 min, which was 68% shorter than the 30-min guideline, while maintaining the same intermittent ventilation effectiveness.
2. For the 12 studied cases, the unit orientation and configuration had a significant impact on the minimized window opening duration, while the daily wind conditions had a relatively minor impact.
3. The proposed smart control strategy for intermittent ventilation can minimize the window opening period so that thermal discomfort and exposure to heat could be minimized, especially for the elderly, in public housing during hot seasons in Hong Kong.

Future research directions include testing the proposed approach in different climatic conditions and implementing the smart control algorithm in real-world applications.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

YS: Conceptualization, Formal Analysis, Writing – original draft, Writing – review and editing. HD: Data curation, Methodology, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ai, Z. T., Mak, C. M., Cui, D. J., and Xue, P. (2016a). Ventilation of air-conditioned residential buildings: a case study in Hong Kong. *Energy Build.* 127, 116–127. doi:10.1016/j.enbuild.2016.05.055

Ai, Z. T., Mak, C. M., Cui, D. J., and Xue, P. (2016b). Ventilation of air-conditioned residential buildings: a case study in Hong Kong. *Energy Build.* 127, 116–127. doi:10.1016/j.enbuild.2016.05.055

Beijing Municipal Health Commission (2022). Guidelines for specialists in home rehabilitation of persons infected with COVID-19. Available online at: http://wjw.beijing.gov.cn/wjwh/ztzl/xxgzbd/gzbdzcfg/202212/t20221207_2872708.html (Accessed December 15, 2024).

Blocken, B., Janssen, W. D., and van Hooff, T. (2012). CFD simulation for pedestrian wind comfort and wind safety in urban areas: general decision framework and case study for the Eindhoven University campus. *Environ. Model. and Softw.* 30, 15–34. doi:10.1016/j.envsoft.2011.11.009

Brown, W. G., and Solvason, K. R. (1962). Natural convection through rectangular openings in partitions—1: vertical partitions. *Int. J. Heat Mass Transf.* 5 (9), 859–868. doi:10.1016/0017-9310(62)90184-9

Census and Statistics Department (2022). *Demographic trends in Hong Kong 1991-2021*. Hong Kong.

Chau, C. K., Tu, E. Y., Chan, D. W. T., and Burnett, J. (2002). Estimating the total exposure to air pollutants for different population age groups in Hong Kong. *Environ. Int.* 27 (8), 617–630. doi:10.1016/s0160-4120(01)00120-9

Cheung, P. K., and Jim, C. Y. (2019). Indoor air quality in substandard housing in Hong Kong. *Sustain. Cities Soc.* 48, 101583. doi:10.1016/j.scs.2019.101583

Chief Executive's Office (2022). *The chief executive's 2022 policy address*. Hong Kong.

Dai, H. K., and Chen, C. (2022). Air infiltration rates in residential units of a public housing estate in Hong Kong. *Build. Environ.* 219, 109211. doi:10.1016/j.buildenv.2022.109211

Dai, H. K., Shi, Y., and Chen, C. (2024). Developing a deep neural network model for predicting ventilation rates in public housing buildings in Hong Kong. *Energy Build.* 307, 113993. doi:10.1016/j.enbuild.2024.113993

Franke, J., Hellsten, A., Schlunzen, K. H., and Carissimo, B. (2011). The COST 732 Best Practice Guideline for CFD simulation of flows in the urban environment: a summary. *Int. J. Environ. Pollut.* 44 (1-4), 419–427. doi:10.1504/ijep.2011.038443

Godish, T., and Spengler, J. D. (1996). Relationships between ventilation and indoor air quality: a review. *Indoor Air* 6 (2), 135–145. doi:10.1111/j.1600-0668.1996.00010.x

Hong Kong Housing Authority (2021). *Housing in figures*. Hong Kong.

Kwok, Y. T., Lau, K. K. L., Lai, A. K. L., Chan, P. W., Lavafpour, Y., Ho, J. C. K., et al. (2017). A comparative study on the indoor thermal comfort and energy consumption of typical public rental housing types under near-extreme summer conditions in Hong Kong. *Energy Procedia* 122, 973–978. doi:10.1016/j.egypro.2017.07.454

Lai, Y., Ridley, I. A., and Brimblecombe, P. (2020). Air change in low and high-rise apartments. *Urban Sci.* 4 (2), 25. doi:10.3390/urbansci4020025

Melikov, A. K., Ai, Z. T., and Markov, D. G. (2020). Intermittent occupancy combined with ventilation: an efficient strategy for the reduction of airborne transmission indoors. *Sci. Total Environ.* 744, 140908. doi:10.1016/j.scitotenv.2020.140908

Mitchell, D., Heaviside, C., Vardoulakis, S., Huntingford, C., Masato, G., Guillod, B. P., et al. (2016). Attributing human mortality during extreme heat waves to anthropogenic climate change. *Environ. Res. Lett.* 11 (7), 074006. doi:10.1088/1748-9326/11/7/074006

Su, W., Ai, Z., Liu, J., Yang, B., and Wang, F. (2023). Maintaining an acceptable indoor air quality of spaces by intentional natural ventilation or intermittent mechanical ventilation with minimum energy use. *Appl. Energy* 348, 121504. doi:10.1016/j.apenergy.2023.121504

United Nations Population Fund (2023). *State of world population report 2023*. New York.

Yang, C., Shi, H., Yang, X., and Zhao, B. (2010). Research on flow resistance characteristics with different window/door opening angles. *HVAC&R Res.* 16 (6), 813–824. doi:10.1080/10789669.2010.10390936