Impact of Window and Air-conditioner Operation Behaviour on Cooling Load in High-rise Residential Buildings

Abstract

Space cooling is an important building energy end-use that was found in recent years to be significantly impacted by occupant behaviours. However, the majority of previous studies ignored the interplay between the operation of windows and air conditioners (ACs) on cooling load, particularly in building energy modelling. In addition, studies on the analysis of cooling load characteristics regarding high-rise buildings are insufficient. The vertical effect of high-rise buildings on cooling load remains vague. This study thus aims to examine how window and AC operation behaviours impact the cooling load of high-rise buildings in an urban context demonstrated by a real-life typical 40-floor residential building in Hong Kong. This study investigates window and AC operation behaviours jointly and examines the vertical effect on cooling load by using agent-based building energy modelling (BEM) techniques and initiating stochastic and diverse behaviour modes. A carefully designed questionnaire survey was conducted to help build behaviour modes and validate energy models. Ninety building energy models were established integrating meteorological parameters generated by the computational fluid dynamics (CFD) programme for ten typical floors and nine combinations of window and AC behaviour modes. The results show that comfort-based AC modes and schedule-based window modes yielded the lowest cooling load. Considering the combined effect of AC and window uses, the maximum difference in cooling loads could be 26.8%. Behaviour modes and building height induce up to 32.4% differences in cooling loads. Besides, a deviation between the behaviour modes and height on the cooling load was found. The findings will help develop a thorough energy model inferring occupants' window and AC behaviour modes along with the building height in high-rise residential buildings. The findings indicate that the interaction impact of window and AC behaviour modes and height should be jointly considered in future high-rise building energy modelling, building energy standards, and policymaking.

Keywords

Occupant behaviour, Air conditioning, Natural ventilation, High-rise residential building, Building energy use

1. Introduction

1.1 Impacts of space cooling

Global energy use in buildings was reported to reach a historical high of 128 EJ in 2019, rising obviously and almost continuously from 118 EJ in 2010 (Abergel and Delmastro 2020). Buildings account for approximately 30% of final energy consumption and 55% of electricity consumption around the world (IEA 2020). The growing demand for building services and extreme weather events contribute much to the increasing energy use in buildings (Abergel and Delmastro 2020). The analysis of energy efficiency in buildings is necessary to satisfy the goals under the Paris Agreement (IEA 2019), which is expected to play a role and mitigate global CO_2 emissions by decreasing end-use energy intensity (IEA 2020). With the flourishing development of air conditioning systems and the improved expectations for the built environment, space cooling is one of the "fastest-growing" building energy end-uses (Abergel and Delmastro 2020). Nearly 8.5% of the final electricity consumption worldwide is attributed to space cooling, and it is estimated that the energy data will increase by 50% if the cooling efficiency is not improved by 2030 (Delmastro 2020). Similar concerns were also raised by Santamouris (2016), who found that the average cooling energy demand of residential and commercial buildings will grow separately by up to 750% and 275% by 2050. Thus, it is urgent to understand the cooling load in buildings to seek balanced solutions between people and the planet.

1.2 Gaps concerning space cooling

However, two gaps exist in the body of knowledge concerning space cooling. The first gap is that although there was some discussion about the interconnection among occupant behaviours (Andersen 2009, IEA/EBC 2013) that influence cooling load, the majority of the previous studies (e.g., Pan et al. (2019)) ignored the interactive operation impact of windows and air conditioners (ACs), particularly in building energy modelling (BEM). Window operation was found to influence the use of ACs. Generally, occupants do not turn on ACs and open windows simultaneously (Yu et al. 2019, Du et al. 2020). Liu et al. (2021) conducted a large-scale field measurement among 34 residential buildings in eight cities in China and found that occupants would close the windows when the AC was turned on. Jian et al. (2022) found that occupants would give priority to open windows for natural ventilation when they feel unsatisfied with the hot indoor environment. Occupants could remain in a hot indoor environment under natural ventilation for a certain period of time before turning on ACs. Also, some studies stated that the state of ACs was an important factor influencing window operation behaviour (Zhou et al. 2018). The overlook of the joint impact of window and AC operation on building energy use would result in the inaccurate inference on the energy impacts of either analysing window or AC operation behaviour separately. For example, as Zhou et al. (2016) pointed out, it would occur error when recognising AC operation behaviour without considering window operation behaviour. The error was that during the short period after the windows were opened in the morning, the air temperature and relative humidity would be dropped simultaneously, and the samples would be recognised as "AC on" which led to the inaccuracy. More studies are needed to identify how the window and AC operation jointly impact space cooling.

The second gap is the insufficient studies with analysis of cooling load targeting high-rise buildings. High-rise buildings are springing up worldwide due to developing economies and the blooming population in recent years (Sayigh 2016, Al-Kodmany 2020). Referring to CTBUH (2020), 77 out of the 100 tallest buildings in the world were established during 2010-2020. Moreover, there are nine cities with more than 100 buildings with over 150 m, including Hong Kong, New York City and Shenzhen. The prospective trend of skyscrapers can be easily captured in Figure 1, and they are believed to dominate future megacities. In addition, high-rise buildings with distinctive building heights (Lotfabadi 2014) are attached to vertically changed microclimatic conditions, such as air temperature, pressure and wind speed, compared to low- or mid-rise buildings. A field investigation in Malaysia (Aflaki et al. 2016) found a more than 1 ℃ difference in air temperature and an approximately 0.2~0.4 m/s difference in air velocity between the living rooms on Floor 3 and Floor 13, indicating a better indoor thermal environment at higher floors in summer (Tyler et al. 2017). Building height was also analysed as a potential influencing factor of building energy use in a large-scale investigation of 611 office buildings in the UK (Godoy-Shimizu et al. 2018). Thus, the default use of "a typical/reference floor/room" in previous studies with low-rise or mid-rise buildings no longer fits studies with high-rise buildings.

1.3 Modelling approaches

Quantitative descriptions of occupant behaviour are necessary for analysing a person's impact on the building energy performance (Peng et al. 2012). Currently, various quantitatively mathematical occupant models in existing studies can be categorised into three models (Ding et al. 2021): fixed model (e.g., Rijal et al. 2008, Xia et al. 2019, Pan et al. 2019), stochastic model (e.g., Zhang and Barrett 2012, Wang et al. 2017), and machine learning (e.g., Mo et al. 2019, Zhang et al. 2021). To explore the relationship between occupant behaviour and building energy performance, researchers have attempted to integrate the operation behaviour models and the building energy simulation software (Hong et al. 2018, Zhong and Ridley 2020). Designer's Simulation Toolkit (DeST) is one of the building energy simulation tools with the integrated dynamic occupant behaviour models developed by the Institute of Environment and Equipment of the Department of Building Technology Science of Tsinghua University (DeST). Also, in order to obtain the outdoor environment parameter values, such as the wind speed outside a particular window, establishing computational fluid dynamics (CFD) models is an effective and efficient method supported with extensive journals (Toparlar et al. 2017).

1.4 Research aim

Due to the above gaps and challenges, the primary novelty of the methodology of this study is to integrate dynamic occupant behaviour models, building energy simulation models, and CFD models to embrace the diversity and stochastics of adaptive behaviours concerning the use of windows and air conditioners, reflect the interaction between the two abovementioned behaviours and consider the different microclimatic conditions at different floors of a high-rise building.

This study thus focuses on the analysis of cooling load characteristic in high-rise residential buildings considering window and AC operation behaviours. Following important questions are addressed:

(1) Considering occupant stochasticity nature, what are the characteristics of window and AC operation behaviours on cooling load in residential buildings? Do window and AC operation behaviours need to be jointly considered?

(2) Is the building height an important factor that influences the cooling load? How to take building height into account in the building energy model?

(3) What is the relationship among various height, window, and AC operation modes on cooling load?

A real-life 40-floor public residential building in Hong Kong was selected in this study. Following this introduction is the overall methodology. Then this paper provides a detailed explanation of the building energy modelling (BEM) considering technical and physical contexts, meteorological context, and behavioural context. The results and analyses are provided based on the BEM. Finally, the paper compares the results with other literature and draws recommendations for reducing the cooling load.

2. Methodology

This study was conducted through onsite questionnaire survey, CFD modelling, and building energy modelling. First, an onsite questionnaire survey was conducted among residents of the target building to collect energy-related data. Next, vertically changed meteorological parameters were yielded for low, mid, and high floors at the target building using the CFD technique. Then, a building energy model with the integration of the meteorological parameters was established, and simulation results were produced for cooling load under multiple combinations of different behaviour modes at different floors.

A Y-shaped 40-floor residential building in Hong Kong located in the hot and humid climate zone was used for the case study. This study used this single case building to demonstrate the procedures and conduct the examinations because this single building was a typical real-life high-rise residential building in Hong Kong with detailed energy-related data and we can integrate the real outdoor environment into the energy model to make the results more reliable in real conditions. In addition, the methods used for this building can be adopted in other studies.

An integrated building energy model (illustrated in Figure 2) was established using case building to examine the impact of window operation behaviours on the cooling load. The integrated building energy model considers three categories of input parameters: technical and physical, meteorological, and behavioural (Figure 2). The multiple data collection approaches and building simulation techniques deployed in the examination are also illustrated in the figure and elaborated hereinafter.

The research steps and their relevant research methods are elaborated below.

An onsite questionnaire survey was applied to the residents of the case building to obtain the associated technical, physical, and behaviour parameters of the model, which included the households' demographic characteristics, possession of household appliances, energy-related behaviour modes, and energy bills. A total of 135 effective answers were received. In particular, the questionnaire results helped to identify three representative operation modes separately for the use of windows and air conditioners. Associated behaviour patterns were achieved, referring to local standards, existing literature and survey results.

The meteorological parameters, including air temperature, relative humidity, wind speed, and wind direction, were collected from a nearby local official observatory (Hong Kong Observatory). In particular, the different microclimatic conditions at different building heights were carefully considered. The wind pressure of openable windows was calculated using computational fluid dynamics (CFD) modelling supported by the Pheonics programme. Other meteorological parameters were processed using empirical formulas in the literature, such as the dry adiabatic lapse rate (DALR).

A DeST-supported integrated building energy model was then established. In this way, the model yielded diverse operation modes of windows and air conditioners and generated cooling loads for households on different floors. The simulation results were validated using energy bills collected through the questionnaire survey and other publicly available data sources such as the Hong Kong government report (Hong Kong Energy End-use Data 2017).

Finally, the impact of window operation modes on the cooling load and associated energy-saving opportunities was discussed within the context of high-rise residential buildings in the hot and humid climate zone.

3. Integrated building energy model

3.1 Technical and physical contexts

Public housing is a major type of housing supply in Hong Kong which accommodates nearly half of the total population in the city (HIF 2021). Modular flat designs (MFD) have been developed by the Hong Kong Housing Authority (HKHA) to enhance the productivity and efficiency of the construction of public housing blocks. Such MFDs specify a total of four types of residential units, which are standardised and consistent in different public housing blocks. These standardised units can be configured according to the site specifics of different projects. Also, because of the scarce developable land supply and high-rise high-density urban environment in Hong Kong, the newly built public housing blocks are normally of around 40 storeys (Qin and Pan 2020). Considering these facts and features, one typical public housing building was selected for this study. This target building is a 40-storey public housing block with standardised MFDs, and the residential units are configured into a Y-shaped floor layout. This building is located in the Kowloon City District of Hong Kong and has been occupied since 2013. To better understand the building energy consumption across floors, a total of 10 flats from different floors were examined in the model. These selected flats were distributed every four floors from Floor 3 to Floor 39 and had relatively good ventilation due to their advantageous orientation. The energy models of typical floors, ground floor, and top floor were built using DeST software.

The building envelope information was set according to the statement in a Hong Kong-based green building assessment method (HKGBC 2012). The U value of the envelope was set as: external walls (U = 3.85 W/m^2K), roofs (U = 0.55 W/m^2K), internal walls (U = 3.72 W/m^2K), slabs (U = 2.89 W/m^2K), and windows (U = 5.78 W/m^2K). Windows were made of single clear glass with a solar heat gain coefficient (SHGC) of 0.775 and visible transmittance of 0.881. These details were verified through experts' focus group meetings in architecture design and building construction in Hong Kong, including experts from developers and contractors and professionals such as architects and sustainable consultants.

The lighting power density was assumed in reference to related criteria in BEAM Plus Version 1.2 (HKGBC 2012), the minimum from Chinese standard GB 50034-2013 (Ministry of Housing and

Urban-Rural Development 2014), and available products in the market (SHEK and LI 2013). Consequently, the room lighting was set as 28 W in the bedroom, kitchen and bathroom; and 70 W in the living room. Lighting density was separately set as 5.6 W/m^2 in the kitchen and bathroom and 3.8 W/m^2 in the bedroom and living room. The lighting schedule was determined by room occupancy and indoor illuminance. Lighting was suggested to turn on when the room was occupied after 18:00 since the sunset time was approximately 17:40 to 19:10 in Hong Kong during the survey period in 2017 (Hong Kong Observatory 2021).

Information on appliance possession excluding air conditioners was obtained through an onsite questionnaire. The description of air conditioners was taken out separately and explained in Section 3.3.2. The appliances in this study did not include heaters since few households have heating equipment in Hong Kong. The operation time of appliances was suggested based on local experience. The input information of the appliances is provided in Table1.

3.2 Meteorological context

This study considered three ambient climatic factors: wind speed, dry bulb air temperature, and relative humidity. Relative humidity of outdoor air changes little with vertical differences based on the record of Hong Kong Observatory. Thus, the vertical differences in these factors except relative humidity on different floors were studied in the energy modelling.

3.2.1 Wind speed and pressure

Outdoor wind speed and pressure were considered through the four steps of the natural ventilation module enabled in DeST software.

The first step is the setting of the natural ventilation control strategy. In this step, the upper and lower air temperature limits of natural ventilation were assumed as 16℃ and 32℃ based on Hong Kong's general temperature range. The upper limit of the relative humidity was set as 80% with the evidence that in Hong Kong, when the weather turns rainy, fogged, or thundery outside, the relative humidity is approximately 80% or above (HKO 2020), and the high humidity outside would make occupants feel discomfort and drive them to close the windows.

The second step is the setting of the ventilation resistance unit, i.e., the settings of the window resistance model and window operation schedule. The window resistance model consists of the window opening and closing resistance models. The window opening resistance model aims to calculate the pressure drop of a certain flow of air through the window when it is open. It was set based on the power-exponential resistance model in this paper (eq.1, eq.2). n was the flow index and was set as 0.5 based on the DeST instruction. The window closing resistance model was set based on the orifice model, aiming to calculate the infiltration air volume through the cracks of the window when the window is closed. Air density ρ was set as 1.2 kg/m^3. C_Q was the flow coefficient, $kg/(s.Pa^{0.5})$, and A was the openable area of windows, m^2. We assume the open ratio of the window was 50%.

$$Q = C_Q \cdot (\Delta P)^n \quad \text{(eq.1)}$$

$$C_Q = 0.622 \times \sqrt{\frac{2}{\rho}} \times A \quad \text{(eq.2)}$$

Window operation schedule was related to occupant behaviour with dynamics and stochasticity. The schedule was elaborated in Section 3.3 behavioural context.

The third step is the setting of the wind pressure coefficient. Wind pressure is the primary driver of natural ventilation. To probe the realistic outdoor environment, such as wind pressure in a specific target window, a CFD model was established by Phoenics software including the target building X and its surrounding buildings within a radius of 200 metres of the target building, displayed in Figure 4. The calculation domain in Phoenics was set as $2000m \times 2000m \times 500m$. The average wind speed of 16 directions with a reference height $86m$ were set as the CFD modelling boundary, which was obtained and calculated from the weather data provided by Hong Kong Observatory. The profile type was the power law (eq.3) with power law index 0.35 considering the conditions of a high-density urban city such as Hong Kong (Ng et al. 2011). v_{met} was the wind speed recorded by the Hong Kong Observatory data at height H_{met} ($H_{met} = 86m$); and H was the height of the measured point in each flat across floors. After simulation, wind pressure P_S at the measured point was obtained from the CFD modelling result. The CFD model considered the impact of the surrounding buildings and produced wind pressure results for different floors. The average wind speed at different heights (v_H) was then calculated using eq.3 in 16 directions, which was converted to wind pressure coefficient C_P (eq.4) to be imported into the DeST model. Air density ρ was set as 1.2 kg/m^3. P_V was the dynamic pressure.

$$v_H = v_{met}\left(\frac{H}{H_{met}}\right)^{\alpha} \quad \text{(eq.3)}$$

$$C_P = \frac{P_S}{P_V} = \frac{P_S}{\frac{1}{2}\rho {v_H}^2} \quad \text{(eq.4)}$$

3.2.2 Outdoor air temperature

The outdoor air temperature across floors was set based on the dry adiabatic lapse rate method (eq.5) which was used in previous research (Lotfabadi 2014), where Γ is the adiabatic lapse rate, T is the temperature at altitude H, g is the standard gravity, and D_p is the specific heat at constant pressure. On the basis of the recording data from upper-air observations on the official website of the Hong Kong Observation (Hong Kong Observatory 2018), Γ was set as 8 ℃/km.

$$\Gamma = -\frac{dT}{dH} = \frac{g}{D_p} \quad \text{(eq.5)}$$

3.3 Behavioural context

Occupant behaviours are related to the operation of windows and air conditioners (ACs) (Yan et al. 2017). This study considered occupants' daily routine, operation modes of window and AC, operation area, cooling season, and the connection between ventilation and space cooling. The living room and bedroom were assumed to have the same window and AC operation behaviour.

3.3.1 Occupants' daily routine

Based on the questionnaire results, a family of three occupants living in one target flat was the most common combination, accounting for 41% of the total target flats, namely, one working people, one unemployed people, and one child. The child and the unemployed people shared the same schedule. Living room was served as the second bedroom in the evening. Two adults slept in the second bedroom and the child slept in the master bedroom (the original bedroom). The assumption of the occupants' daily routine is displayed in Figure 5. Workday was from Monday to Friday, and Rest day was from Saturday to Sunday.

Additionally, by considering the stochastic and dynamic of the occupant behaviour, both the probability for staying in one room and the staying duration was set based on the occupant schedule of the questionnaire results (Yu et al. 2019). The probability of the child staying in the master bedroom/living room/outside was set as 0.8/0.1/0.1. The probability of the working and unemployed people staying in their second bedroom/outside was set as 0.944/0.056 and 0.883/0.117, respectively. Each stay lasted 120 minutes in their relative bedrooms and 20 minutes in other places.

3.3.2 Operation models of window and AC

This study delivered energy simulation for a total of ninety scenarios in this case building, considering the combination of three window operation modes, three AC operation modes, and ten floors. The cooling season was assumed to start from May and end after October based on the questionnaire results about the operation period of air conditioners. The formulas of the operation modes of windows and ACs in living rooms and bedrooms are summarised and illustrated in Table 2 and Table 3, respectively. The columns "Triggers" in Table 2 and Table 3 represent the triggers of the operation of ACs and windows. The empirical patterns of each trigger were drawn from the questionnaire results and the literature. The associated questions in the questionnaire enable multiple choices.

Window operation behaviour

Window operation behaviour was identified to be related to multiple factors. Jeong et al. (2016) found that occupants' daily activities had a strong relationship with the window operation behaviour. Andersen et al. (2013) investigated 15 Danish residential buildings and found that indoor CO_2 concentration and outdoor temperature were the key factors in relation to window operation behaviour. Calì et al. (2016) examined the window operation behaviour of 60 apartments in Germany in 2012 and concluded that the time of the day, room CO_2 concentration, room air temperature, outdoor temperature and relative humidity were the most important factors. Du and Pan (2021) adopted an in-situ monitoring method to investigate window and AC behaviour in a university dormitory in Hong Kong and found that window operation behaviour was mostly event-based. According to our study context, Hong Kong, which has a hot and humid climate, room air temperature or outdoor temperature would be related to AC and window operation behaviour. Thus, given the above considerations, time of day, room CO_2 concentration, outdoor air temperature, and relative humidity were selected as the key factors of opening/closing windows.

In total, three window operation modes were initiated based on occupants' daily activities, which were also the top three answers with the highest probability in the questionnaire (displayed in Figure 6): 1) keep windows open all day; 2) keep windows open during the daytime; and 3) open windows for a while after getting up in the morning. At each time, behaviour modes were associated with the triggers of indoor CO_2 concentration and outdoor relative humidity. Thus, as displayed in Table 2, window operation modes were integrated with both event and environmental triggers in bedrooms and living rooms. Three modes were proposed, i.e., long-duration mode (W1), middle-duration mode (W2), and short-duration mode (W3). A three-parameter Weibull distribution was adopted to illustrate the influence of room CO_2 concentration. As the natural ventilation control strategy showed in Section 3.2.1, the upper limit of relative humidity was 80%, and the upper and lower air temperature limits were 16℃ and 32℃, respectively. The range of indoor CO_2 concentrations was between 1000 ppm and 2000 ppm. According to the ASHRAE standards, the lower limits of 1000 ppm satisfies 1000 to 1200 ppm in spaces housing sedentary people (ASHRAE 2016). The upper limit of 2000 ppm was based on the upper limit for safe levels of CO_2 in rooms (KANE 2020). The parameter of "k" was assumed to be 3.7 since 1500 ppm was the mean average CO_2 level (assumed 50%) in a field examination in the high-rise residential bedrooms in Hong Kong (Lin and Deng 2003).

AC operation behaviour

According to the questionnaire results, as displayed in Table 4, AC operation modes can be categorised into three levels: comfort-based, schedule-based, and mixed. The mathematical models for these three AC operation modes are illustrated in Table 3. A three-parameter Weibull distribution was adopted to illustrate the influence of indoor air temperature. The temperature to turn on the AC when feeling hot was assumed to start at 18℃ (u=18) and end at 35℃ (l=17) based on answers about the "feeling hot" temperature with 25 effective samples. The parameter of "k" was assumed to be 4.2 in reference to the questionnaire results indicating that approximately 64% of the occupants would turn on AC at 28℃. Similarly, the temperature to turn off AC when feeling cold was assumed to range from 18℃ to 27℃, and other parameters were determined (u=27, l=9, k=2.5) by the fact that 70% of occupants would turn off AC at 23℃ with 23 effective samples. Occupants were believed to behave in the same way in the bedroom and living room. The probabilities of the modes "turn on before sleeping" and "turn off after getting up" were assumed based on the related input in previous studies (Ren et al. 2014). The input parameter (l=120, k=2) of "turn off when leaving home" was also in reference to previous studies (Sun et al. 2016). The setpoint temperature was assumed to be 24℃, which was the median of the general setpoint temperature in the questionnaire results.

In addition, the operation of windows and AC was assumed to be mutually exclusive in this study, which means that occupants could not simultaneously keep windows open and AC on. The questionnaire results supported this exclusionary relationship in that more than 80% of the occupants would not open windows and operate AC simultaneously.

4. Results and analyses

Multiple data sources were used for model validation to ensure the reality and effectiveness of both operation rules and simulated building energy consumption. Energy data sources for validation involve offical energy data released by the Hong Kong government (e.g. Hong Kong Energy End-use Data 2017), energy bills from the questionnaire survey, and the total electricity metered data from the display board in the lobby of the target building. Different behaviour modes were analysed to ensure reasonable and representable occupant operation habits. Then, the results were analysed from three perspectives: cooling load by different behaviour modes, cooling load by building height, and cross-analysis with behaviour models and building height. Underlying reasons for the different cooling loads were also explored.

4.1 Model validation

4.1.1 Estimated results of the building energy models

Figure 7 shows that the estimated cooling load ranges from 112 kWh/m^2 to 166 kWh/m^2, with an average value of 138 kWh/m^2 during the summer period in the household. In order to be comparable with the data from other sources, the cooling electricity consumption was calculated based on the simulated cooling load and the coefficient of performance (COP) of the installed window-type AC. The AC product used in the bedroom and living room was labelled as grade one according to the production lists of the room air conditioners in Hong Kong. Window-type ACs with rated COP 2.8 were installed in the bedroom and living room of the target flats and have been operated since 2015. Changeable COP with hours was considered in this paper. The COP performance curve of window-type AC for the context of Hong Kong was calculated by the equation (eq.6) calibrated by Chen et al. (2008). The annual electricity consumption was thus calculated by the equation (eq.7).

$$COP = \frac{r \times Q_R}{W_R \times (r + w_F)} \quad \text{(eq.6)}$$

$$E_{annual} = \sum_{i=1}^{n} \frac{Q_i}{COP_i} = \sum_{i=1}^{n} \left(\frac{Q_i \times W_R}{Q_R} + W_R \times w_F \right) \quad \text{(eq.7)}$$

Where, r refers to the load ratio, $r = \frac{Q_i}{Q_R}$; Q_R refers to the rated cooling capacity; W_R refers to the rated power input; $w_F = 0.0585$ refers to the normalised fixed power input for the window-type AC; n refers to the total hour during the whole cooling season, n=4416; Q_i refers to the cooling load at ith hour; COP_i refers to the COP at ith hour.

Therefore, the average annual cooling consumption of the ninety models was estimated as 67.8 kWh/m^2. Similarly, the average cooling consumption in the hot and transition season was estimated as 11.6 and 9.4 kWh/m^2 per month, respectively.

4.1.2 Validation of the building energy models

The aim of the validation is to 1) ensure that the proposed window and AC operation modes are reasonable, and 2) ensure that the simulated cooling load is acceptable and reliable. Validation was investigated in three steps.

First, the general performance of the models was examined logically. We should ensure that the building requires more cooling load during the hot month. Figure 8 displays the trend of the mean cooling load changing with outdoor temperature. The mean monthly outdoor temperature was obtained through the official website of the Hong Kong Observatory (Hong Kong Observatory 2021). The monthly cooling load displays a rather similar trend to that of the monthly outdoor temperature. It is reasonable in Hong Kong that the cooling load peaks in August and reaches the bottom in May. Also, we expected that the occupant behaviour modes functioned reasonably. We examined the export result files on both the operation rules and their cooling load performance to ensure the rules and performance run normally and fit our proposed scenarios. We found that the total window opening hours for W1 (long-duration), W2 (middle-duration), and W3 (short-duration) modes were in descending order, which meets the operation rules. Another example is that residents operate more ACs than windows during hot days. The cooling load of the operation rules were verified from the distribution of cooling consumption from energy bills and simulated results, as displayed in Figure 9. Based on the distribution of cooling consumption from the energy bill and simulated results, we can see that the simulation results of ninety cases were all within the highest probability range in the energy bill results (45-85 kWh/m^2). Besides, different behaviour modes showed distinct performance on cooling consumption, reflecting different operation habits.

Since this building is a typical public housing block in Hong Kong, the comparison between the energy use data of this building and the data released by the Electrical and Mechanical Services

Department - EMSD of the Government is useful. According to the Hong Kong Energy End-use Data released by the EMSD in 2017, the electricity consumed in the residential sector was 1614 kWh per capita in 2015. One capita occupied 13.1 m^2 on average in 2015 in public residential buildings (THB 2020). The total electricity consumption was thus calculated as 123.2 kWh/m^2. It is noted that the metered data was 116 kWh/m^2, exhibiting a 5.8% difference compared with the official data released by the EMSD of Hong Kong Government, which shows that the target building can reasonably reflect the general energy use pattern in Hong Kong.

Third, the estimated cooling load was compared to the actual energy bills and metered data (Table 5), involving the annually cooling electricity consumption and average cooling consumption in hot/transition months. For the annually cooling electricity consumption, the total electricity consumption from the energy bills was obtained by residents with a total number of 124 effective answers and was calculated by household according to the residential tariff calculation on the official CLP power company website in Hong Kong. Since the cooling electricity consumption accounted for approximately 30% of the total electricity consumption in the public housing sector in 2015 (Hong Kong Energy End-use Data 2017), the cooling electricity consumption from energy bills can be estimated as 58 kWh/m^2/year. Similarly, the metered data of cooling electricity consumption can be estimated as 34.8 kWh/m^2/year. The simulated annual average cooling consumption was 67.8 kWh/m^2, close to the energy bills (58 kWh/m^2). For the average cooling consumption in hot/transition months, we collected the energy bills for hot/transition months from the questionnaires. Thus, the residents consume 12.6/7.9 kWh/m^2 per month of the electricity consumption in the hot/transition season. The simulated average cooling consumption in hot/transition months was estimated as 11.6/9.4 kWh/m^2, close to the data from the energy bill (12.6/7.9 kWh/m^2).

4.2 Cooling load by different behaviour modes

The cooling load under different behaviour modes was found to be completely different (Figure 7). During the summer period, W1AC2, W2AC2, and W3AC2 presented the highest cooling load, while W1AC1, W2AC1 and W3AC1 needed the least cooling supply, and W1AC3, W2AC3, and W3AC3 were in between. The highest cooling load occurred in W2AC2 on Floor 3, and the lowest cooling load occurred in W3AC1 on Floor 39.

The results indicate that schedule-based AC modes generally have the highest cooling load, followed by mixed AC modes and comfort-based AC modes in descending order. Compared with window operation modes, the influence of AC operation modes on the cooling load was dominant in all cases. W1, i.e., long-duration mode, showed a higher cooling load than W2 and W3. The main reason for the higher cooling load under the W1 mode is that frequent openings of the window result in the inhalation of enough hot fresh outdoor air to increase the indoor air temperature and reach the trigger point to turn on the AC, thus increasing the AC operation time during the whole summer period. An example demonstrates this based on the data from W1AC1 and W2AC1 on Floor 3 in the living room reported on August 20th. For W1AC1, both the window (450 min) and AC (810 min) operated more than those for W2AC1 (window 270 min, AC 780 min). W1AC1 had a higher cooling load (0.90 kWh/m^2) than W2AC1 (0.82 kWh/m^2).

The transition season usually refers to the start and end of the summer period, when opening windows is likely to result in the inhalation of cold outdoor air to cool down the indoor air temperature. Natural ventilation can then provide free cooling and help to decrease the total cooling load. For example, as Figure 10 displays, on May 2nd on Floor 7 in the bedroom with W1AC1 modes, from 0:00 to approximately 7:00 and 10:30 to the end of that day, the outdoor air temperature was lower than the indoor air temperature with the window open, which means that the outdoor air indeed cooled down the room.

The hottest month and the typical transition month (August and May, as the evidence displayed in Figure 8) were separately selected to conduct a further comparative analysis to differentiate the free cooling impact.

During the typical summer month, as displayed in Figure 7, the performance of all behaviour modes shared a similar trend compared with that during the whole 5-month period, demonstrating that in the typical summer month, the schedule-based AC operation mode produced more cooling load. This is mainly due to the massive use of AC under the schedule-based AC mode. Under the same AC operation mode, occupants with the long-duration window operation mode produced the highest cooling load. The principal cause is that opening windows introduced hot outdoor air, and thus, the increased indoor air temperature triggers the use of AC.

During the typical transition month (Figure 7), compared with the results in August, the overall cooling load was generally lower under each behaviour mode due to less dependence on space cooling. Similar to the results in the hottest month, the schedule-based AC mode (AC2) again had the most significant impact on the cooling load, followed by the AC3 mode and AC1 mode. The difference between the AC1 mode and AC3 mode is due to the turning off mode of air conditioners. Under the AC1 mode, occupants would turn off AC "when hot inside", while under AC3 mode, occupants would turn off AC "when leaving home or after getting up". It can be deduced that in transition month, the indoor air temperature was lower than that in hot month, which increased the probability of turning off AC and enlarged the difference of these two modes on cooling load.

Since the living room and bedroom have different room functions and occupant schedules, the performance of these two rooms is distinct. This study then compared the cooling load by different behaviour modes separately in the two spaces. Floor 3 was selected as the case floor to maintain consistency as in the former analysis. According to the in-situ investigation, the living room served as the "living room" in the daytime and the "bedroom" at night for two adults. Figure 11 shows the cooling load of different modes in the bedroom on Floor 3 during the whole summer period, typical hot month, and typical transition month.

Three findings can be generated by analysing the results presented in Figure 11.

First, the living room had a higher cooling load than the bedroom for all behaviour modes. This is mainly because occupants prefer to stay in the living room, thus increasing the AC running time. For example, as Figure 12 displays, the duration of time that occupants stayed in the bedroom within one entire day was much lower than that in the living room. As a result, the cooling load in the bedroom is lower than that in the living room.

Second, occupants with the W1 mode required more space cooling than others under the same AC operation modes. The cooling load performance of the W2 mode and W3 mode was approximately equal. This indicates that opening the window all day is the least energy-efficient mode. The varied natural ventilation duration causes the cooling load difference under the same AC operation mode.

Third, in the bedroom, the cooling load under the AC2 mode was much larger than that under the other two AC modes, showing that the schedule-based AC operation mode resulted in a higher cooling load. The other two AC modes, AC1 and AC3, which more or less involved individual feelings of occupants, generally showed more frequent turning on/off of AC to meet their comfort requirements. Such frequent operation behaviours would shorten the AC operation time and result in less cooling load.

The difference in cooling load by behaviour modes (R_{modes}) was identified in eq.8. Associated results are illustrated in Table 6.

$$R_{modes} = \frac{E_{max} - E_{min}}{E_{max}} \quad \text{(eq.8)}$$

where,

R_{modes} (%) indicates the difference in cooling load under different behaviour modes at the same height.

E_{max} (kWh/m^2) means the maximum cooling load at the target floor.

E_{min} (kWh/m^2) means the minimum cooling load at the target floor.

The difference in cooling load by behaviour mode can reach as high as 26.8% during the whole summer period. Generally, the difference in behaviour modes was even more remarkable in transition months than in hot months.

4.3 Cooling load by building height

Figure 13 demonstrates the cooling load of different behaviour modes under different heights. Several findings can be described. First, the cooling load was found to decrease with increasing height under all behaviour modes. Second, different modes shared different cooling loads on the same floor. Third, AC operation control was the dominant factor compared with the window operation control that influenced the cooling load. Fourth, the slope of the fitting curve of each operation mode was slightly different, which shows that the impact of height on the cooling load in different modes was different.

As displayed in eq.9 and Table 7, the difference in cooling load by building height can reach 8.3% during the whole summer period. The difference in cooling load by building height in the typical hot month was slightly lower than that in the typical transition month.

$$R_{Floor} = \frac{E_{F3} - E_{F39}}{E_{F3}} \quad \text{(eq.9)}$$

where,

R_{Floor} (%) indicates the difference in cooling load between Floor 3 and Floor 39.

E_{F3} (kWh/m^2) means the cooling load under Floor 3.

E_{F39} (kWh/m^2) means the cooling load under Floor 39.

The difference in cooling load by height is mainly explained by the changing outdoor environment with height causing different window or AC use. For example, under W1AC1 mode, the cooling hours in the living room on Floor 3 and Floor 39 were 2085.5 h and 2055.5 h, respectively, and the window operation hours were 2073 h and 2114.5 h, respectively. This result suggested that occupants living on Floor 3 operated AC more but operated windows less. The introduced hot outdoor air may quickly increase the indoor air temperature and increase the AC operation time. As AC operation was the determinant factor of the cooling load, households at higher floors with lower outdoor air temperature would consume less energy for cooling.

4.4 Cross analysis with behaviour modes and building height

Behaviour modes were mainly triggered by environmental and event factors. Environment means indoor environment changes such as the increase of indoor temperature when individuals were staying for a while. Event means schedule-based human activities such as the time required for getting up and leaving home. The two types of factors were found to be interconnected with each other, as displayed in Figure 14.

An example shows the interconnection starting from the action of opening windows. When individuals open the window, the AC is turned off accordingly, and outdoor air is introduced into the room. The concentration of indoor CO_2 decreases thereafter. The next occupants' action towards the window or AC partly depends on the humidity and temperature of the outdoor air. If it is humid outside, the indoor relative humidity will increase, and occupants may find the indoor environment unsatisfactory and would close windows. If it is hot outside, the indoor air temperature would increase and reach the AC threshold. The action of turning on AC leads to the action of closing the window and would therefore increase the indoor CO_2 and decrease the indoor air temperature. If the concentration of indoor CO_2 reaches the threshold of action to open the window, the window would be opened. If it is not sufficiently hot outside to make the indoor air temperature reach the AC operation threshold, the state of window opening will persist unless the three window closing incentives above are triggered.

As displayed in Figure 7 in Section 4.1, the cooling load ranged from 112 kWh/m^2 to 166 kWh/m^2 with a difference of up to 32.4%. The difference in cooling load was caused by both the height and the operation behaviour of windows and AC. Behaviour modes contributed to the difference in cooling load by up to 26.8% (see Table 6), and the height by up to 8.3% (see Table 7). The combined impact of the height and behaviour modes on the cooling load makes up the remaining difference.

Figure 15 shows the conceptual calculation method for the causes of the cooling load difference. The deviation refers to the additional deviation caused by considering the height and behaviour modes at the same time, which is the sum of the height effect (R_f) and behaviour mode effect (R_m) minus the overall difference (R_{all}). Table 8 shows the results of the overall annual cooling load on different behaviour modes and heights in descending order.

Thus, through calculation, $R_f(R_m)$ ranges from 0.7% to 8.3% (0.0% to 26.8%). R_{all} ranges from 1.1% to 32.4% and $R_{deviation}$ ranges from 0.0% to 1.5%. From these results, it can be found that the difference between various floors and behaviour modes varies greatly. This indicates that in some situations with low R_{all}, it is not necessary to consider the effect of these various modes and floors on the cooling load since the change in the cooling load is negligible.

5. Discussion

The results and findings of this study are discussed from three perspectives, i.e., the overall methodological approach, suggestions regarding BEM, and recommendations for reducing the cooling load.

5.1 Overall methodological approach

This study adopted multiple data collection methods, including the results from an onsite survey and questionnaire results in one real-life high-rise residential building together with the summarised typical empirical models drawn from the questionnaire and the literature, which is scientific and effective. Onsite survey data and questionnaire data make the building data more in line with the real situation, so that compared with hypothesis building, the results of this case building have more guiding significance for realistic circumstances (Du and Pan 2021). The summarised typical empirical models, which draw from both the questionnaire and the literature, allow the case building to showcase the energy performance under different high probability scenarios of AC and window behaviour modes, which is meaningful to other similar buildings. The high probability scenarios of the behaviour modes were selected based on the top three answers with the highest probability in the questionnaire survey. This study did not have in-situ monitoring of occupant behaviour, indoor or outdoor environments measurements due to two major reasons. On the one hand, the synthesised behaviour modes based on the questionnaire survey, local standards and previous studies were functional and effective enough to reflect the cooling load of different users in residential buildings in Hong Kong. It is less necessary to conduct additional in-situ monitoring activities for obtaining behaviour patterns, such as the setpoint temperature of space cooling. On the other hand, simulated results of the target building are to showcase the general energy performance of local households with different operation habits. It is more important to set proper representations of different behaviour modes than to catch the real-life differences of certain behaviour modes between households through long-term in-situ monitoring activities. In this way, the findings of this paper will be applicable to a wider range of regions other than just fitting for the target building.

With multiple data collection methods, this study weakens the analysis of the actual occupant behaviour of ACs and windows in this case building, but strengthens the analysis of the most conventional occupant behaviours of ACs and windows in the whole Hong Kong region, making this study more widely applicable. In addition, the conventional building energy simulations generally adopt a fixed or rule-based schedule for occupant behaviours. This kind of simplification fails to reflect the stochastic nature of occupant behaviour and will reduce the accuracy and reliability of the building energy simulation results (Hong et al. 2016, Nord et al. 2018). Although some studies have concentrated on building energy performance related to windows or AC operation behaviour, this study carefully considered the stochasticity and dynamics of the interaction between windows and AC operation behaviour to represent the stochastic nature of occupant behaviour, which has seldom been examined in previous studies.

In addition, to analyse the height effect via different behaviour modes on cooling load, this study calculated the outdoor environment of each floor through the CFD model and then integrated the simulated outdoor environment into the energy simulation model. This integrated method reflects the actual outdoor environmental conditions and can help analyse the relationship between the outside environment and occupant behaviour on cooling load (Du and Pan 2021) and can be applied elsewhere. The integration of the building energy simulation and CFD can eliminate simplification assumptions in each model and provide a more accurate prediction of building performance (Zhai and Chen 2006). This study showed the necessity of using this kind of integration when examining energy performance in high-rise buildings. The results showed a great variety of cooling load performances at different heights and behaviour modes, which cannot be ignored. Although the integration of building energy simulation and CFD is not new, previous studies have paid little attention to adopting this integrated method in research on floor-based window operation modes and cooling loads.

5.2 Suggestions regarding building energy modelling

Two suggestions regarding BEM were made according to the results of the study.

First, full consideration of outside environmental factors is recommended in modelling cooling loads when the building height is greater than specific floors. In this study, building height between Floor 3 and Floor 39 can result in an 8.3% difference in building cooling load. This percentage is considerable and cannot be neglected. However, buildings with less than 30 floors, in which the height can only influence less than 5% of the total cooling load reported in this study, do not have to consider the height impact when modelling energy. In such buildings, the building height is not a significant factor influencing the cooling load. The convenient measure to consider the outside environment in building energy modelling is to integrate the CFD results into the energy simulation models. Therefore, when modelling the energy of high-rise buildings with less specific floors, in this case, on Floor 30, there is no need to conduct CFD simulation to integrate height impact into the energy modelling.

Second, when modelling the cooling load of high-rise buildings, considering the interaction impact of both behaviour modes and height is highly suggested in future related studies. The impact of various behaviour modes and heights on the cooling load can have a wide range from a minimum of 1.1% to a maximum of 32.4%. If the interaction impact is not fully considered, the results of the impact of behaviour modes (height) on cooling load in this study can be between 0.0% and 26.8% (0.7% and 8.3%), which is inaccurate and cannot reflect the whole. Additionally, an additional deviation of behaviour modes and height was found in this study. Despite the small impact of the additional deviation on the cooling load (up to 1.5%), this study proved the existence of a deviation between the behaviour modes and height. The results indicating a 32.4% difference in cooling load caused by behaviour modes and height are adapted to the region of Hong Kong where the climate is typical subtropical. The findings of this study can be taken as a reference in Hong Kong because the selected building is a typical public housing block in Hong Kong, which has a rather similar geometry to other public residential buildings and many private high-rise residential buildings in Hong Kong. The findings of this study can also be applicable to other subtropical cities. The AC and window operation modes summarised from the questionnaire survey and previous studies in the literature can be a reference in Hong Kong or even a wider range of regions (e.g., Singapore). Thus, studies of buildings in other subtropical cities with similar climates can regard this present paper as a useful point of reference. Such difference due to various behaviours and floor heights can be greater for hotter regions (such as Malaysia and Africa) and lower for mild-climate places (such as Yunnan Province in southwest China). However, the results would be different if the location is changed to Beijing or Moscow in cold weather. Different countries and regions can have largely different climates, and lifestyles can also change with culture and environment. For example, our study did not consider space heating since the questionnaire survey results showed that heating devices were rarely used in local households in Hong Kong. However, in cold regions such as Beijing and Moscow, both space cooling and space heating should be considered and thus there may be discrepancies in results compared with this present study.

5.3 Recommendations for reducing the cooling load

To reduce the cooling load, three recommendations were proposed.

First, opening windows in transition months to allow natural ventilation, particularly at high floors, could be an effective measure to reduce the indoor air temperature and save cooling load in subtropical regions. This suggestion is also proven by other studies, such as that of Schulze and Eicker (2013). In addition, households tend to open windows more at higher floors, which can be supported by previous studies such as Schweiker et al. (2012). This means that households on the higher floors can more easily receive natural ventilation to save cooling load since the outdoor air temperature is lower than that on the lower floors. In this study, by using the CFD technique, the outdoor air temperature on Floor 39 was found to be approximately 1 degree higher than that on Floor 3. This free cooling technology is applicable in subtropical climatic regions such as Hong Kong.

Second, a lower frequency of opening windows in hot months is recommended. This study showed that opening windows in hot months would increase the indoor air temperature and thus trigger the use of AC. As Figure 16 shows, in this study, opening windows all day (W1 mode) used a higher cooling load, approximately 3% to 6%, compared with the other two modes on each floor. Opening windows in hot months was found to increase the cooling load and thus have a negative impact on cooling load conservation and thermal comfort maintenance. Also, the consistency of the cooling load with floors shows the linear relation to the input parameters. The reason is mainly attributed to the descending linear relation of outdoor hot air temperature with floors. Households at lower floors with higher outdoor air temperature would have more probability to trigger the use of AC. As AC operation was the determinant factor of the cooling load, households at lower floors during the typical hot month would consume more energy for cooling.

Third, comfort-based AC operation modes use less energy than the schedule-based and mixed modes. With the schedule-based or mixed operation modes, occupants usually operate the AC over a long period of time compared with comfort-based occupants. For example, in this study, occupants operated 2085.5.5 hours of AC with comfort-based mode (AC1), which was 44% lower than that with the schedule-based mode (AC2, 3726 hour) during the whole summer period, assuming the same window operation modes in the living room on Floor 3. Therefore, households are recommended to turn on or off AC based on their comfort feelings which both satisfies their comfort needs and saves energy.

6. Conclusions

This paper has investigated the impact of window and AC operation behaviours on the cooling load in high-rise residential buildings, demonstrated through a real-life 40-floor public residential building in Hong Kong. Ninety energy simulations were established with three window operation modes and three AC modes at ten typical floors of the building. Energy modelling was supplemented by a carefully designed questionnaire survey and integrated by floor-based outside environmental factors through CFD modelling. The innovation of this study involves the joint examination of window and AC operation behaviours, using agent-based BEM techniques and initiating stochastic and diverse behaviour modes, and the consideration of different floors in high-rise buildings. The conclusions of the paper are drawn as below:

- The effects of window and AC behaviour modes on cooling load should be jointly considered. Window and AC behaviour modes can cause a 26.8% difference in cooling load. Among the various window and AC behaviour modes, comfort-based AC modes and schedule-based window modes have the lowest cooling load, and they are highly recommended.
- Building height is an important factor when modelling high-rise building energy performance.

The cooling load can decrease by up to 8.3% as the height increases. A flat on a higher floor with a lower outdoor air temperature has less cooling load. Also, it is worth noting that buildings with less than a specific height (e.g., 30 floors in this study), in which the height can only influence less than 5% of the total cooling load, do not have to consider the height impact when modelling energy.

- The effect of the window, AC behaviour modes and heights on the cooling load should be jointly considered when buildings with more than a specific height. With the combination of behaviour modes and height, the cooling load was observed to show a 32.4% difference. Also, a deviation between the behaviour modes and height on the cooling load was found.

The findings indicate that the interaction impact of window and AC behaviour modes and height should be jointly considered in the future high-rise building energy modelling, building energy standards, and policymaking. The findings will also help develop a thorough energy model inferring occupants' window and AC behaviour modes along with building height in high-rise residential buildings.

This paper has several important implications. Theoretically, this paper has examined window and AC operation behaviours jointly with various heights in the context of cooling load using agent-based BEM techniques and by initiating stochastic and diverse behaviour modes, filling the gaps in previous studies. This combined method could provide more reliable and accurate building energy results and is recommended in future studies when modelling high-rise building energy performance. Methodologically, this paper has provided a multicollection method involving drawings and documents from architects, onsite questionnaire surveys, government documents, and previous studies, making the input data and output results reliable and reasonable.

Future research can examine the effect of behaviour modes on cooling load in high-rise offices or commercial buildings and analyse the differences in energy performance among various types of high-rise buildings. Additionally, this study has some limitations. The meteorological data were obtained from the nearest observatory which was several kilometres away from the location of the case building, and this may have caused some disparities in the results. If possible, the better practice is to measure the case building's meteorological parameters instead of obtaining these data from the observatory.

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