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https://doi.org/10.1007/s12273-022-0934-8

Research Article

Residential building performance analysis at near extreme weather conditions in Hong Kong through a thermal-comfort-based strategy

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Abstract

The precise building performance assessment of residential housings in subtropical regions is usually more difficult than that for the commercial premises due to the much more complicated behavior of the occupants with regard to the change in indoor temperature. The conventional use of a fixed schedule for window opening, clothing insulation and cooling equipment operation cannot reflect the real situation when the occupants respond to the change in thermal comfort, thus affecting the appropriateness of the assessment results. To rectify the situation, a new modeling strategy in which the modification of the various operation schedules was based on the calculated thermal comfort (TC), was developed in this study. With this new TC-based strategy, the realistic building performances under different cooling provision scenarios applied to a high-rise residential building under the near extreme weather conditions were investigated and compared. It was found that sole provision of ventilation fans could not meet the zone thermal comfort by over 68% of the time, and air-conditioning was essential. The optimal use of ventilation fans for cooling could only help reduce the total cooling energy demand by less than 12% at best which could only be realistically evaluated by adopting the present strategy. Parametric studies were conducted which revealed that some design factors could offer opportunities for reducing the total cooling energy under the near extreme weather conditions.

Keywords

predicted mean vote;
thermal comfort;
ventilation potential;
building performance simulation;
residential housings

Article History

Received: 29 May 2022
Revised: 03 August 2022
Accepted: 19 August 2022

Building Thermal, Lighting, and Acoustics Modeling

1 Introduction

Building systems contribute a major proportion of electricity demand in a modern city. In particular, the HVAC systems consume a significant amount of energy. Hence, the study of building energy performances is normally one of the key directions of research for energy saving and reduction in carbon emissions especially for commercial buildings due to their higher internal loads and usual provision of air-conditioning throughout the year. The study of residential buildings, although comparatively less extensive, does not seem to be easier due to the variations in occupant behaviors and/or habits in response to a change in the indoor thermal comfort. These include changes in window opening, clothing and operation of different types of cooling/heating equipment. In face of global warming, the optimal use of natural ventilation for the minimization of cooling energy demand is also a major concern, particularly in a subtropical region in which the period for hot and warm seasons is substantial.

Most current researches on the thermal performances of residential buildings are based on pre-set schedules for window opening, clothing and operation of air-conditioning equipment. Chan (2012) employed EnergyPlus to investigate the effect of adjacent shading on the thermal performances of residential buildings and impact of floor level on the shading effect of a balcony (Chan 2015). In both studies, fixed window opening and air-conditioning operating schedules were selected. Chen et al. (2016) also used EnergyPlus in combination with genetic algorithm to determine the optimal design of a residential building for maximal indoor environmental quality. They did not consider the influences

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List of symbols

1P0B	single-person open flat	POE	post occupancy evaluation
2P1B	single-bedroom flat for two persons	S	south wing
4P2Ba–c	double-bedroom flat for four persons	S1–S4	different scenarios of cooling provision
ACH	air change per hour	SAT	Saturday
BR	bedroom	SUN	Sunday
E	east wing	T	toilet
K	kitchen	TC	thermal comfort
LDR	living and dining room	W	west wing
N	north wing	WD	weekday
PMV	predicted mean vote		

from occupants and operating schedules of active building systems. Cheung et al. (2015) developed a hybrid approach using EnergyPlus and artificial neural network to predict the cooling energy demand of public housing in Hong Kong under different building envelope designs. A controlled indoor environment was considered under a fixed zone temperature without natural ventilation. Du et al. (2016) investigated the effect of building envelope thermal storage on the thermal performance of a bedroom during nighttime. Window opening schedule was not taken into account, and only a fixed ventilation rate was specified with air-conditioning provided under a fixed schedule. Yu et al. (2019) compared the simulation results of a residential building based on conventional settings of occupant behaviors and the other one using post occupancy evaluation (POE) data. Shi et al. (2019) studied the effect of urban microclimate on the cooling energy demand of a residential building. All windows were assumed closed with an assumed infiltration rate of 0.5 air change per hour (ACH) and air-conditioning was provided under a fixed schedule. Gan et al. (2019) conducted an optimization study using genetic algorithm on the design layout plan for residential buildings for minimal cooling energy demand. They considered both the cases with (all windows opened and air-conditioning offered when indoor temperature exceeded setpoint) and without (all windows closed and air-conditioning always on) natural ventilation. Yu et al. (2020) investigated the impacts of various passive cooling techniques on the cooling energy demand of a residential building. Air-conditioning was not operated between November and March inclusive and the window opening depended on the outdoor temperature with maximum at 32 °C and minimum at 18 °C.

As seen, the common way of modeling the energy performance of residential housings may not cohere well with the actual occupant behaviors. Besides, the use of only indoor or outdoor temperature to govern the operation of the air-conditioners may not truly reflect the comfort level of the building zones. Hence, a better approach can be the adoption of thermal comfort (TC) to determine the operating status of the building systems. One common index for indoor thermal comfort is the predicted mean vote (PMV). Studies on PMV-based building system management can also be found which were mainly limited to the control of active systems like an air-handling unit (Tse and So 2000), a variable-air-volume system (Kang et al. 2010), a cooling system (Hwang and Shu 2011), a heating system (Hawila et al. 2018) and a direct expansion air-conditioning system (Yan et al. 2018) rather than a building operation strategy. Moreover, limited researches mentioned about the revision of the clothing insulation throughout the simulation period. Hence, this was the intent of this study to develop a new simulation strategy based on the zone PMV which governed the schedules of window opening, clothing insulation and operation of cooling equipment in order to resemble the actual response of occupants to a change in indoor thermal comfort. With this new strategy, the performance of a residential building under different cooling provisions was analyzed and the results compared. Parametric studies were also conducted to investigate the effects of various design strategies on the cooling energy demand of the building.

2 Building description

A typical high-rise residential building as shown in Figure 1 was considered. This is one of the common designs used for the public housings in densely-populated Hong Kong. Each floor of the building comprises various flat configurations which range from the one-person open flat without bedroom (1P0B), the single-bedroom flat for two persons (2P1B) to the two-bedroom flats for four persons (4P2Ba–c). These also represent the majority of small-unit private residential building configurations and can thus be considered as typical designs for small residential flats. In this study, only the east wing on the 7th floor (typical floor) of the building as shown in Figure 1 was investigated. The performances at other wings can be simulated by rotating the east wing

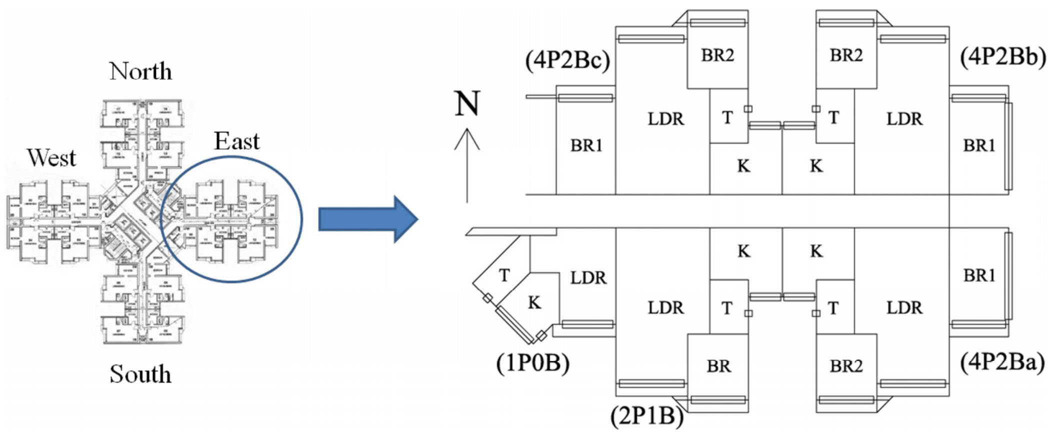

Fig. 1 Layout of a typical high-rise residential building

through suitable angles. Each flat consists of a kitchen (K), a toilet (T), a living and dining room (LDR) as well as bedroom(s) (BR) where applicable.

3 Building specifications

The materials used for the building facade in accordance with Kwok et al. (2017) was adopted. The floor-to-floor height was 2.7 m with a floor level of 18.9 m above the ground for the typical floor investigated. The window-to-wall ratio for the bedroom(s), the living and dining room, the toilet as well as the kitchen was taken as 40% according to Chen et al. (2016). All windows were located at 1 m above the floor level. The openable-window-to-floor area ratio was 1/16 according to the local practice in Hong Kong (BD 2016). Plain glass was used for the windows. All windows were closed when the flats were unoccupied. When the flats were occupied, the windows at the kitchen and toilet were 20% opened. The selection of 20% was based on the provision of a threshold air change upon replied trials. For the bedrooms and living and dining room, they were fully opened unless the respective zone PMV was below −0.5 and that the outdoor air temperature was below 28 °C. In such case, the windows would be 20% opened. More elaboration would be given in Section 4. When air-conditioning at respective areas (except kitchen and toilet) was switched on, the windows in that area would be closed.

Figures 2 to 4 show the occupancy schedules for the various flat types. For the living and dining room, the schedules were different among weekdays (WD), Saturday (SAT) and Sunday (SUN). For the other areas, the schedules were the same throughout the whole week. The doors for the kitchen, toilet and bedroom(s) were closed when in use. Otherwise, they would be fully opened. In case air-conditioning was switched on in the living and dining room, all doors would be closed. Lighting was provided at the kitchen, toilet as well as the living and dining room when occupied. For the bedrooms, lighting was only switched on at the last hour of the day. Table 1 summarizes the equipment load utilized in the building. The sizing of the window type air-conditioner was based on the local guideline (EMSD

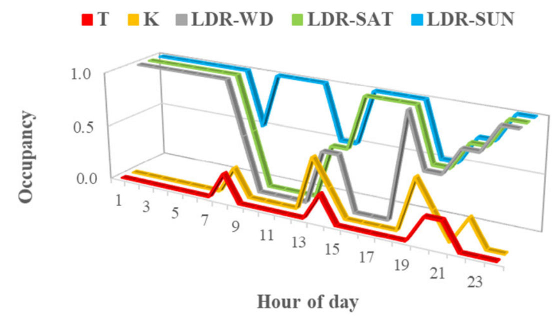

Fig. 2 Occupancy schedules for one-person open flat

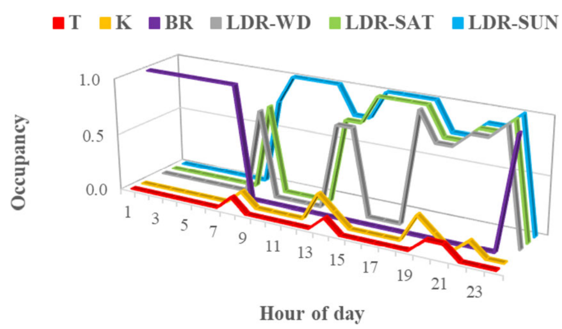

Fig. 3 Occupancy schedules for single-bedroom flat

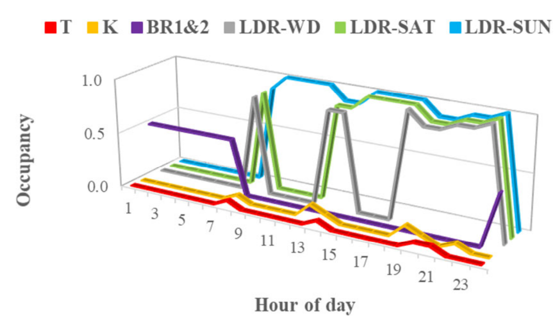

Fig. 4 Occupancy schedules for two-bedroom flat

Table 1 Summarized equipment loads of the building

Type	Value
Gas cooking	1.91 kW for breakfast (0.25 hour for 1P0B and 2P1B; 0.5 hour for others) 3.47 kW for lunch and dinner (0.5 hour for 1P0B and 2P1B; 0.75 hour for others)
Exhaust hood	240 W
Hot water pot	75 W
Refrigerator	120 W
Washing machine	440 W
Panel TV	60 W
Desktop computer	220 W
Fan	50 W
Lighting	6.54 W/m^2 [Energy label Grade 3 (EMSD 2020)]

2022). Here, Grade 3 energy label unit was selected with an average coefficient of performance of 3.325 (EMSD 2020).

The selection of the clothing insulation was critical to the proper modeling of the building. Here, minimum values of 0.36 clo and 1.38 clo were chosen according to ASHRAE (2013) and Lin and Deng (2008) when the occupants were awake and sleeping. The actual clothing insulation might be modified depending on the calculated zone PMV as detailed in Section 4.

4 Algorithm of the TC-based building performance simulation strategy

As mentioned in Section 1, the common use of fixed schedules for windows opening, clothing insulation and operation of cooling equipment could not reflect the actual behavior of the residents in response to the variation of the indoor thermal comfort. Consequently, a new approach was developed as shown in Figure 5 in which the variation of the respective schedules depended on the calculated PMV of the building zones. As cooling was not provided in the kitchen and toilet, the new TC-based strategy was only applicable to the living and dining room as well as the bedroom(s). Four cooling scenarios were considered, namely S1–S4 as detailed below:

S1: no cooling provision.

S2: ventilation fan provided only.

S3: ventilation fan or air-conditioning provided when necessary.

S4: only air-conditioning provided.

For S1, no consideration for the operation ventilation fan and air-conditioning was made and the process moved to the checking of window opening and clothing after the first building simulation as shown in Figure 5. For S2, the process was directed to the checking of window opening and clothing after the checking for operation of high fan speed and re-run of building simulation. For S4, checking for fan operation was bypassed.

The open-source programme Python (Version 3.7.3) under the Spyder (Version 3.3.6) platform was employed to execute the new TC-based building performance simulation strategy in which the dynamic building simulation software EnergyPlus (Version 9.4) was called to run the building simulation numbers of times as shown in Figure 5. The various operating schedules were saved in files which would be read by EnergyPlus during the building simulation. At the beginning, the default schedules as mentioned in Section 3 were adopted. Then, building simulation was performed with the results saved to a file. The PMV of each time step with occupancy were checked if cooling should be provided according to the procedures as indicated in Figure 5 in several steps. The air velocities inside the building zones were assumed to be 1, 1.5 and 2 m/s for low, medium and high fan speeds respectively. The corresponding energy consumption at low and medium fan speeds were taken as 60% and 80% of that at high fan speed as indicated in Table 1. Each time the fan operating schedule was updated, building simulation was re-run with revised results generated. When the fan speed had been set to high and that the PMV was still above 0.5, air-conditioning would be switched on. To simulate a more realistic practice, the operation of the air-conditioner during the whole sleeping period was solely determined by the PMV of the first time step of the sleeping period.

With all the operation of cooling equipment updated, the check for window closing was followed as shown in Figure 5. Here, only the windows at the living and dining room as well as the bedroom(s) were considered whenever occupied. In case the calculated PMV and ambient temperature were below −0.5 and 28 °C respectively, the windows would be shut down to 20% opened. After that, the clothing insulation schedule was reviewed. Again, only those time steps with occupancy in the living and dining room as well as the bedroom(s) were considered. When the PMV's at individual time steps were still below −0.5 after the revision of the window opening schedule, the respective clothing insulation would be increased by 0.1 clo with the building simulation re-run. The process repeated until the PMV's of all the occupied time steps were above −0.5. The complete algorithm was then come to an end.

5 Methodology of analysis

With the algorithm of the new TC-based building performance simulation strategy developed, the indoor thermal comfort and cooling energy demand of the reference residential building were investigated. The control setpoint for the air-conditioner was taken as 25 °C. The SRY weather data

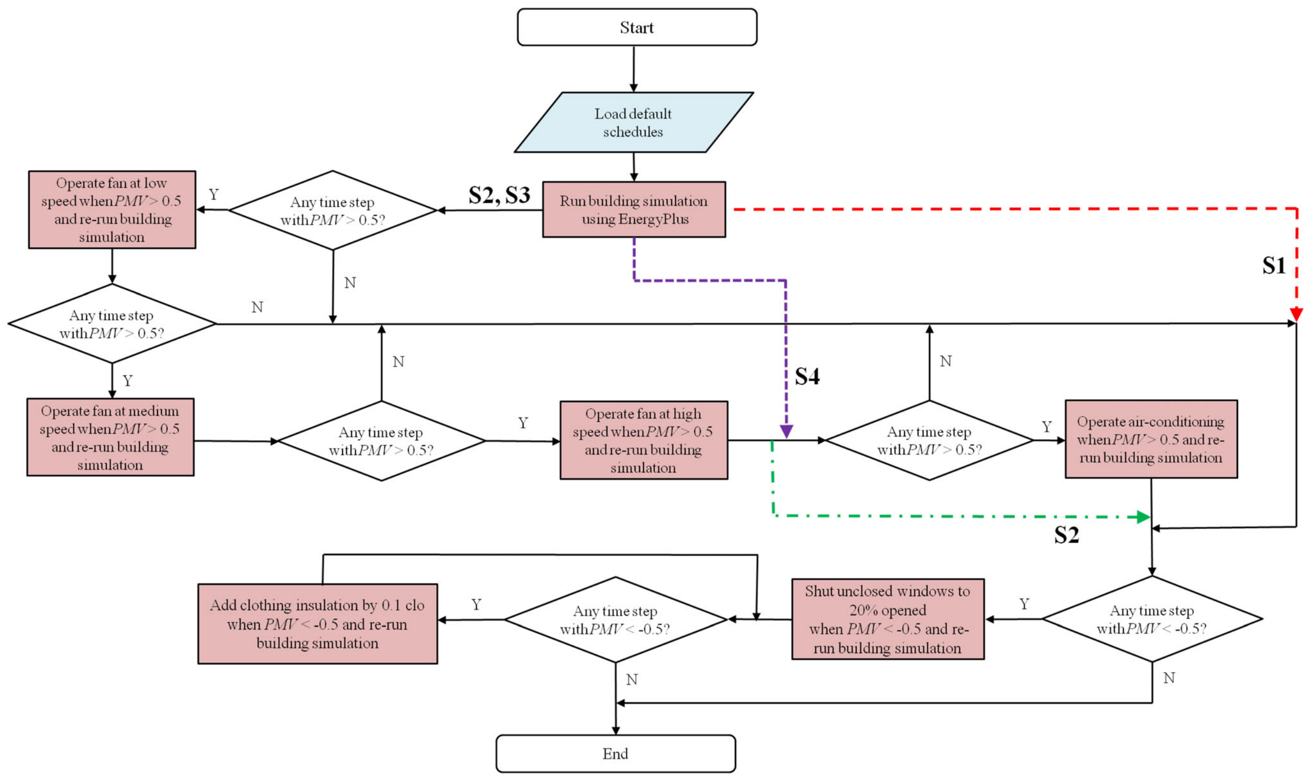

Fig. 5 Algorithm of the TC-based building performance simulation strategy

from May to September inclusive from Kwok et al. (2017) were employed to study the building performance during the hot seasons. The indoor temperatures, PMV's, ventilation potential and cooling energy demand were taken as the parameters for comparison where applicable. As mentioned in Section 2, only the building performance at the east wing would be simulated. To further elucidate the impact of the extreme hot weather, only the building facade for the east wing was built. In this way, the self-shading effect from other building wings could be eliminated.

With the building performance investigated based on the building setting as indicated in Section 3, parametric studies were then conducted in which various design factors were

Table 2 Summarized schedules for the parametric analysis of various design strategies

Design factor	Selection
Building wing	East[1], south, west, north
Provision of balcony	No[1], yes
Provision of vent window	No[1], yes
Floor-to-floor height	2.7 m[1], 3.1 m, 3.4 m, 3.7 m
Floor level	7/F.[1], 14/F., 21/F., 28/F.
Wind speed	Typical[1], 2/3 typical, 1/3 typical, no wind
Window glass	Plain[1], tinted, LowE, tinted LowE
Openable-window-to-floor area ratio	1/16[1], 3/32, 1/8

[1] Base case.

considered to explore their influence on the cooling energy demand as summarized in Table 2. For the balcony, it would be added outside the windows of the LDR with a floor area of 2 m (W) × 1 m (D) and surrounded by a glass of height 1 m. For the vent window, it would be 30% in area of the openable windows. When any design strategy was investigated, the base selections for the other design strategies would be adopted except the building wing. As the cooling energy demand was taken as the parameter for comparison, S1 would not be considered in the parametric studies.

6 Results and discussions

6.1 Building performances under S1

Table 3 summarizes the building simulation results for the typical residential building without any cooling provision. It could be found that the thermal comfort was the worst at the kitchen for all flats with the PMV nearly 100% above 0.5 and temperature over 95% above the critical temperature [set at 29.5 °C according to Cheng and Ng (2006)]. The high equipment load was the main cause even though the averaged zone ACH was also the highest at the kitchen (besides BR1 of 4P2Ba&b). The toilet was the second to the kitchen due to the lowest ACH achieved. The thermal comfort in BR1 of 4P2Ba&b appeared to be the best as there were windows

Table 3 Summarized building simulation results under S1

Building zone	Averaged zone temperature (°C)	Percentage of time with zone temperature above 29.5 °C (%)	Averaged zone PMV	Percentage of time with zone PMV above 0.5 (%)	Averaged zone ACH
1P0B-LDR	31.6	83.2	2.41	98.0	10.9
1P0B-K	35.0	98.1	3.33	100.0	12.7
1P0B-T	33.0	91.0	2.87	99.1	2.23
2P1B-BR	29.1	47.9	1.51	90.4	8.46
2P1B-LDR	30.8	75.7	2.05	95.8	7.99
2P1B-K	33.6	96.0	2.85	100.0	9.70
2P1B-T	31.2	77.8	2.08	95.6	3.63
4P2Ba-BR1	28.2	26.2	1.33	85.4	32.5
4P2Ba-BR2	29.2	48.9	1.52	90.7	8.52
4P2Ba-LDR	30.3	68.2	1.92	93.0	6.44
4P2Ba-K	33.6	94.8	2.90	100.0	13.9
4P2Ba-T	31.5	82.1	2.14	96.4	2.60
4P2Bb-BR1	28.4	30.3	1.37	86.4	26.1
4P2Bb-BR2	29.2	48.6	1.53	90.9	8.56
4P2Bb-LDR	30.5	69.3	1.96	93.7	4.85
4P2Bb-K	33.6	95.1	2.92	100.0	13.9
4P2Bb-T	31.5	82.4	2.15	96.7	2.46
4P2Bc-BR1	29.2	49.5	1.58	92.8	8.48
4P2Bc-BR2	29.2	48.7	1.53	91.0	8.57
4P2Bc-LDR	30.7	74.4	1.99	95.7	8.03
4P2Bc-K	33.7	95.8	2.93	100.0	14.0
4P2Bc-T	31.4	80.7	2.12	96.4	3.56

on two sides of the walls. The BR1 in 4P2Ba was the most comfortable one in view of the much higher ACH. Still, the PMV was above 0.5 for over 85% of time and that the zone temperature was over 29.5 °C by at least 26% of the time. The results indicated that under the near-extreme hot weather conditions, the indoor thermal comfort was very unsatisfactory if no cooling equipment was provided.

Figure 6 indicates the variation of the zone temperatures of 4P2Ba over a continuous hot week. It could be found that the zone temperatures were generally over the critical temperature even at night. Indeed, the daily peak temperature kept increasing over the first 5 days. The situation was similar even at night. This was extremely unfavorable and cohered with a recent study from CUHK (2020) which highlighted the impact of consecutive hot nights to the occupants. From Figure 6, the zone temperatures climbed up by nearly 2 °C during the time when the flats were unoccupied. The reason was that during these periods of time, all windows were closed. Hence, there was limited ventilation inside the flats which could relieve the temperature build-up from the heat transfer through the building envelope. To improve the situation, small vent windows might be used so that air circulation could still be maintained at certain level during the unoccupied period.

Figure 7 shows the variation of the zone PMV's of 4P2Ba over May. The PMV's during the cool days with outdoor temperature dropped to below 25 °C was maintained above −0.5 which highlighted the strength of the present TC-based approach by modifying the window opening and clothing insulation schedules at appropriate time steps in order to maintain the zone thermal comfort to a satisfactory level.

6.2 Building performances under S2

Table 4 shows the simulation results with ventilation fans provided only. As only the living and dining room as well as the bedroom(s) were equipped with ventilation fans, the results for kitchen and toilet were excluded. Compared with Table 3, it could be found that the operation of the ventilation fans did not reduce the zone temperature although the PMV was decreased. The reason was that the running power of the fans would be converted to internal heat load. Consequently, the zone temperature was increased mildly. Meanwhile, the higher zone air speed helped lower the PMV. Nevertheless, there was still over 68% of the time when the PMV was over 0.5 with the averaged PMV dropped to 0.9 at the lowest. Hence, the sole use of fans to provide cooling was considered insufficient.

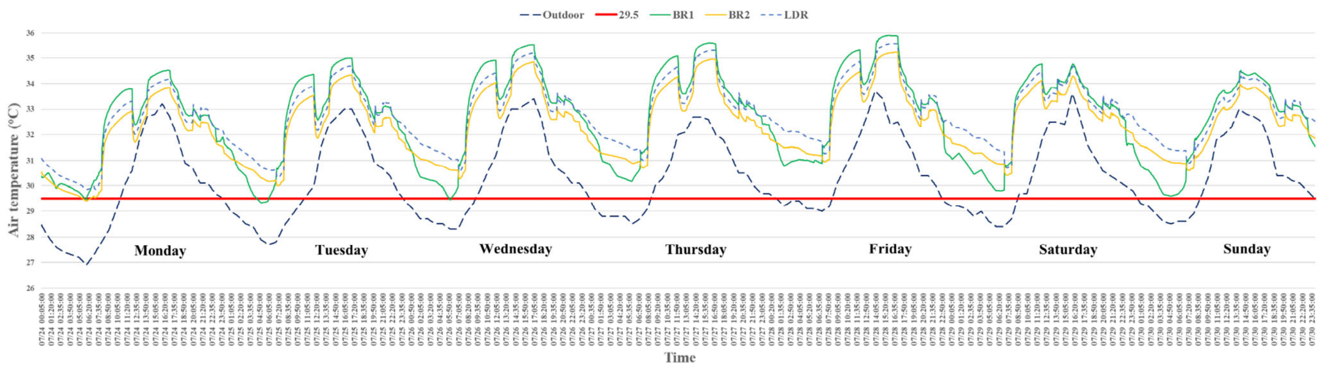

Fig. 6 Variation of zone temperatures of 4P2Ba over a continuous hot week in July

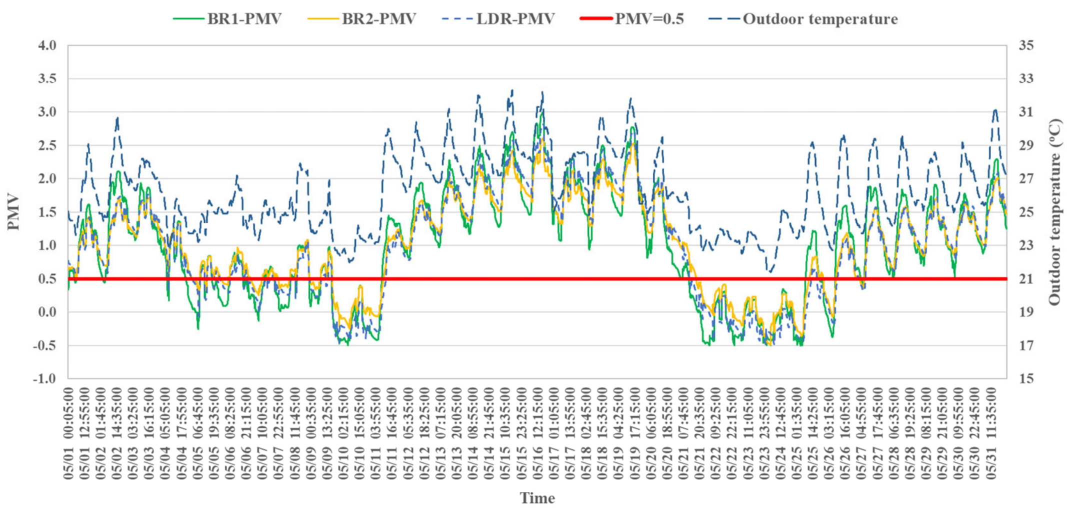

Fig. 7 Variation of zone PMV of 4P2Ba over May

Table 4 Summarized building simulation results under S2

Building zone	Averaged zone temperature (°C)	Percentage of time with zone temperature above 29.5 °C (%)	Averaged zone PMV	Percentage of time with zone PMV above 0.5 (%)	Averaged zone ACH
1P0B-LDR	32.2	87.8	2.33	91.9	11.6
2P1B-BR	29.4	56.4	1.22	81.5	8.97
2P1B-LDR	30.9	76.9	1.51	76.6	8.09
4P2Ba-BR1	28.3	29.3	0.90	68.0	32.6
4P2Ba-BR2	29.4	56.8	1.23	82.0	8.99
4P2Ba-LDR	30.4	69.3	1.28	69.2	6.43
4P2Bb-BR1	28.5	33.8	0.95	68.8	26.2
4P2Bb-BR2	29.4	55.4	1.24	80.9	9.03
4P2Bb-LDR	30.6	70.2	1.34	69.9	4.83
4P2Bc-BR1	29.4	54.7	1.24	81.6	8.89
4P2Bc-BR2	29.5	55.6	1.24	81.4	9.05
4P2Bc-LDR	30.8	75.5	1.41	74.3	8.02

Figure 8 depicts the variation of the monthly-averaged PMV for 4P2Ba under both S1 and S2. In terms of magnitude, the reduction in the monthly-averaged PMV was the highest for LDR followed by BR1. The maximum drop all occurred in September.

6.3 Building performances under S3

Table 5 shows the corresponding simulation results with the provision of ventilation fans and air-conditioning when necessary. Clearly, with the use of air-conditioning, the zone

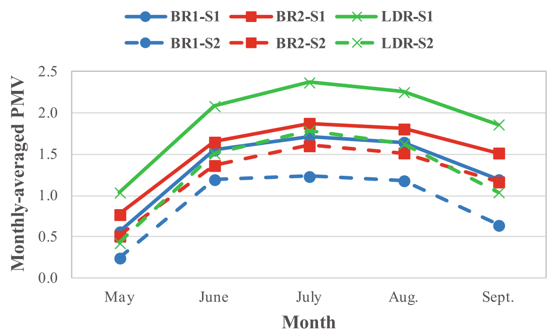

Fig. 8 Profiles of monthly-averaged PMV for 4P2Ba under S1 and S2

temperatures and PMV's were generally kept at the desired levels. The average air temperatures at the living and dining rooms were higher than those of the bedrooms. The reason was that the bedrooms were occupied only at night. Hence, the zone temperatures tended to be lower during the time when only ventilation fans were operated. On the other hand, the living and dining rooms were usually occupied at mid-day. This led to a higher average temperature in the living and dining room. Nevertheless, the differences were at least smaller than the situation when only ventilation fans were used. From Table 5, air-conditioning was required in the bedrooms for over 93% of the time when cooling was provided. Meanwhile, it was less than 80% of the cooling time in the LDR's (except for 1P0B as the LDR also served as bedroom) when air-conditioning was switched on. The reason was due to the much higher clothing insulation threshold for sleeping as mentioned at the end of Section 3.

6.4 Building performances under S4

Compared to S3, the main difference in the building performance was the cooling energy demand when S4 was adopted besides a further reduction in the zone ACH. Table 6 summarizes the building cooling energy demand of various flats under different cooling provision scenarios. With only fans provided, 4P2Bc consumed the most of the cooling energy in comparison with the other two-bedroom flats of 4P2Ba and 4P2Bb. The main reason was the substantially lower cross-ventilation as already indicated in Tables 3 and 4. However, the situation became different when air-conditioning was provided. While the extra windows in BR1 of 4P2Ba and 4P2Bb induced more natural ventilation when they were opened, they would in turn generate higher thermal transmission loads to the bedrooms when they were closed. This explained why 4P2Bc consumed less cooling energy as compared to 4P2Ba and 4P2Bb when air-conditioning was provided. Indeed, similar finding could be observed by comparing the cooling energy demand between 1P0B and 2P1B. The results implied that an increase in the window area did not necessarily enhance an overall cooling energy saving through the employment of the present TC-based modeling strategy.

To validate the simulated energy consumption for air-conditioning, comparison was made with those found in the literature (Wan and Yik 2004). According to Wan and Yik (2004), the surveyed air-conditioning energy demand for residential building was 45–50 kWh/m^2. Based on 4P2Ba in S4 from Table 6 and that the total floor area was 38.2 m^2 for LDR and BR's, the corresponding air-conditioning energy demand was 32.8 kWh/m^2. However, it should be noted that the COP of the air-conditioners during the survey study (around 2.3) was lower than that adopted in the present analysis (3.325). Hence, by taking an adjustment with reference to the COP difference, the respective air-conditioning energy demand became 47.4 kWh/m^2 which agreed with the

Table 5 Summarized building simulation results under S3

Building zone	Averaged zone temperature (°C)	Averaged zone PMV	Percentage of time with zone PMV above 0.5 (%)	Percentage of cooling time with air-conditioner switched on (%)
1P0B-LDR	25.3	0.14	1.98	93.1
2P1B-BR	25.1	0.10	2.04	99.4
2P1B-LDR	25.8	0.12	4.99	79.4
4P2Ba-BR1	25.0	0.19	6.03	99.5
4P2Ba-BR2	25.1	0.12	2.14	99.3
4P2Ba-LDR	25.9	0.20	7.11	74.0
4P2Bb-BR1	25.0	0.18	6.05	99.5
4P2Bb-BR2	25.1	0.12	2.47	99.3
4P2Bb-LDR	26.0	0.20	8.03	74.0
4P2Bc-BR1	25.1	0.06	1.99	99.3
4P2Bc-BR2	25.1	0.11	2.31	99.3
4P2Bc-LDR	25.9	0.14	5.51	77.1

Table 6 Summarized building cooling energy demand

Flat	Total cooling energy demand under different scenarios (kWh)		
	S2	S3	S4
1P0B	136	756	770
2P1B	127	782	862
4P2Ba	175	1120	1252
4P2Bb	177	1114	1243
4P2Bc	183	1039	1142

survey study. Hence, the validity of the simulated energy demand was confirmed.

The total cooling energy demand between S3 and S4 differed only mildly with at most less than 12% for 4P2Ba and 4P2Bb. This was due to the fact the operating time for the ventilation fans was indeed short as already indicated in Table 5. This finding could be revealed only through the use of the present new TC-based building simulation strategy which highlighted its strength in analyzing the realistic HVAC system performance in residential buildings particularly in subtropical regions.

6.5 Effects of different design factors on the building cooling energy demands

6.5.1 Building wing

Figure 9 shows the total energy demand at different building wings under various cooling scenarios. It should be reminded that the direction indicated in the figure refers to the wing position rather than the main facade direction. For S2, the variations among different wings were mild as only ventilation fans were used. Indeed the operating hours of the fans were long particularly between June and August inclusive when the monthly-averaged PMV was the highest as previously shown in Figure 8. Still, it could be found that for 1P0B, 2P1B and 4P2Ba, the total cooling energy was the highest at the south wing (S) when the main facade of the respective flats was facing the West. Meanwhile for 4P2Bb and 4P2Bc the total energy reached the maximum at the north wing (N) when the main facade of the said flats was also facing the west. For S3 and S4, the total energy demands at the south and north wings were comparably higher than those at the east (E) and west (W) wings. Generally speaking, the selection of an optimal building orientation could at most reduce the total cooling energy by over 15%.

6.5.2 Provision of balcony

Figure 10 summarizes the cooling energy reduction by using balcony at different building wings and cooling scenarios. It could be found that the energy saving potentials of using the balcony were the highest in the south and north wings regardless the cooling scenarios. The reason was that for both wings, the main facade of the flats was either facing the east or the west where the shading effect by the balcony was more pronounced. Nevertheless, the maximum cooling energy saving was less than 3%.

6.5.3 Provision of vent window

Figure 11 summarizes the cooling energy reduction by using vent window at different building wings and cooling scenarios. It could be found that with the inclusion of air-conditioning in S3 and S4, the provision of vent window resulted in an increase in the total cooling energy by at most 5%. To explain, the provision of vent window helped enhance the air ventilation during the time when the flats were unoccupied as remarked at the end of the second paragraph in Section 6.1 which led to a reduction in indoor temperature. However, the increase in air ventilation also meant that more moisture would be brought to the indoor. Consequently, the air cooling load during the time when air-conditioning started to be used might become higher, particularly if air-conditioning had already been switched on before the unoccupied period. For S2, the use of vent window could reduce the indoor temperature particularly during the unoccupied period and hence could decrease

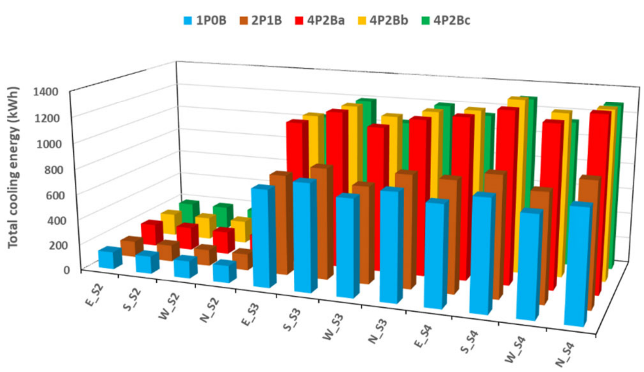

Fig. 9 Summarized total cooling energy at different building wings and cooling scenarios

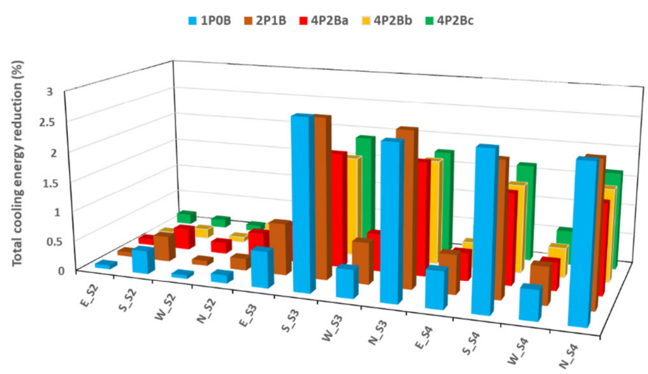

Fig. 10 Summarized cooling energy saving using balcony at different building wings and cooling scenarios

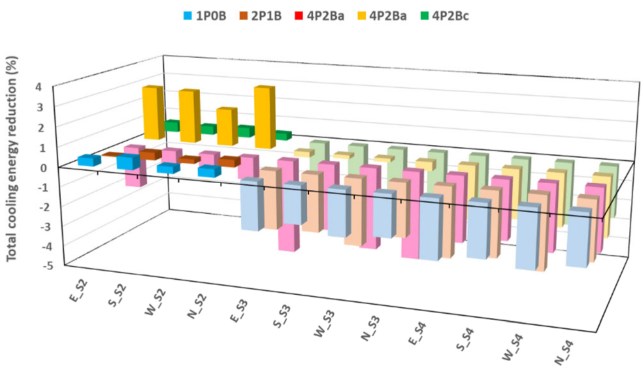

Fig. 11 Summarized cooling energy saving using vent window at different building wings and cooling scenarios

the operating time (and substantially the energy demand) of the ventilation fans which measured up to more than 3%.

6.5.4 *Floor-to-floor height*

Figure 12 indicates the corresponding parametric study results for floor-to-floor height. Without the provision of air-conditioning as in S2, the increase in floor-to-floor height helped improve the ventilation potential of the buildings. Hence, the cooling energy decreased with an increase in the floor-to-floor height although to a limited extent of less than 2%. However, the situation was completely different when air-conditioning was provided. A higher floor-to-floor height led to a higher transmission load through the building facade and hence a higher cooling energy demand of up to 16%.

6.5.5 *Floor level*

Figure 13 shows the parametric study results for floor level. In general, a higher floor level resulted in a lower cooling energy demands and hence a higher energy saving potential due to a lower ambient temperature. Among the three cooling scenarios, S3 yielded the highest cooling energy reduction which measured up to 7% followed by S4.

6.5.6 *Wind speed*

Figure 14 shows the impact of wind speed on the cooling energy reduction at different buildings wings and cooling scenarios. In most cases, the reduction in wind speed led to an increase in the total cooling energy by at most 7%. Only in few situations would the total cooling energy be decreased with a lowered wind speed to an extent of up to only 2%.

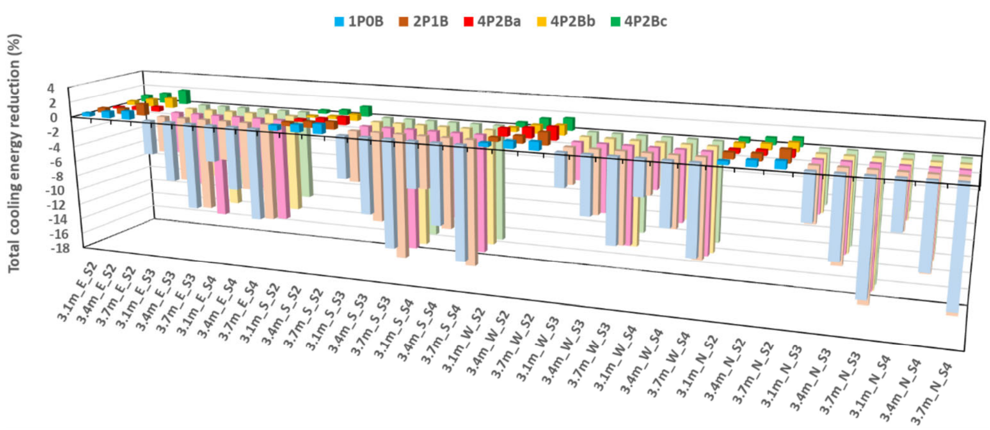

Fig. 12 Summarized cooling energy saving at different floor-to-floor heights, building wings and cooling scenarios

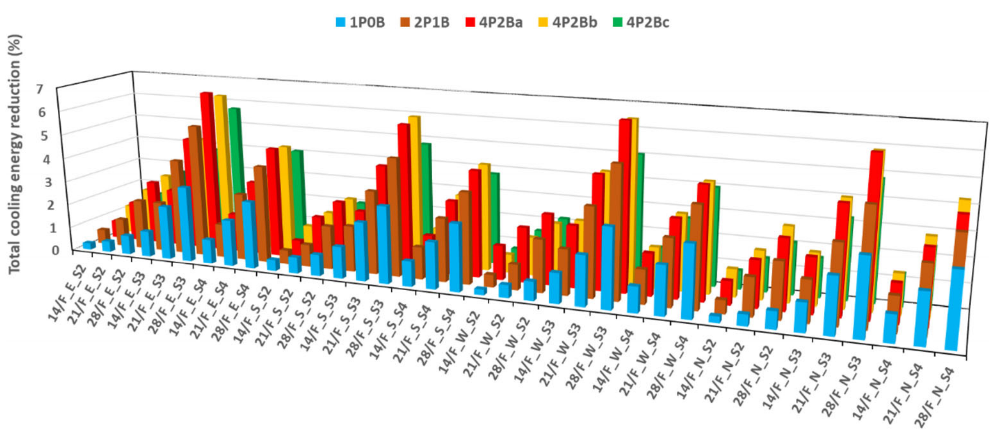

Fig. 13 Summarized cooling energy saving at different floor levels, building wings and cooling scenarios

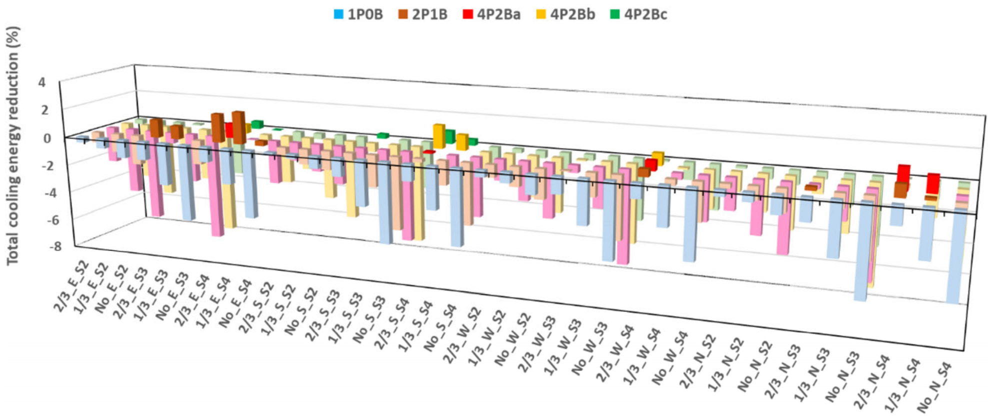

Fig. 14 Summarized cooling energy saving at different wind levels, building wings and cooling scenarios

The effect of wind speed was generally the lowest in S2 and highest in S3.

6.5.7 *Window glass*

Figure 15 indicates the cooling energy reduction by using different glass types. It could be found that energy saving was nearly guaranteed by using better glass types under all cooling scenarios investigated. The tinted LowE glass was the best among the three glass types considered which could achieve more than 12% reduction in the total cooling energy. Again, the savings were the highest in S3 followed by S4.

6.5.8 *Openable-window-to-floor area ratio*

Figure 16 depicts the parametric study results for different openable-window-to-floor area ratio. Clearly, the increase in the openable-window-to-floor area ratio was positive in the cooling energy saving regardless the cooling scenarios adopted although the peak occurred in S3 which measured up to around 8% in S3.

From the above parametric studies, some factors appeared to be positive in reducing the total cooling energy. They are the building orientation, use of balcony, floor level, window glass type and openable-window-to-floor area ratio. These factors can thus be regarded as possible heat mitigation strategies against extreme hot weather for high-rise residential buildings.

7 Conclusion

In this study, a novel thermal-comfort-based building simulation approach was developed for realistically analyzing the building performance of residential housings in subtropical Hong Kong during the hot seasons from May to September inclusive. The window opening, clothing and operation of cooling equipment were adjusted according to the indoor thermal comfort at each simulation time step which imitated the actual behavior of occupants. A high-rise residential building was selected to represent a typical group of small-unit accommodations for the investigation. Different cooling provision scenarios were considered and the results compared. It was found that without any cooling equipment facilitated, the indoor thermal comfort could not be fulfilled by over 85% of the time. The situation was even worse during a continuous hot week with the indoor temperature

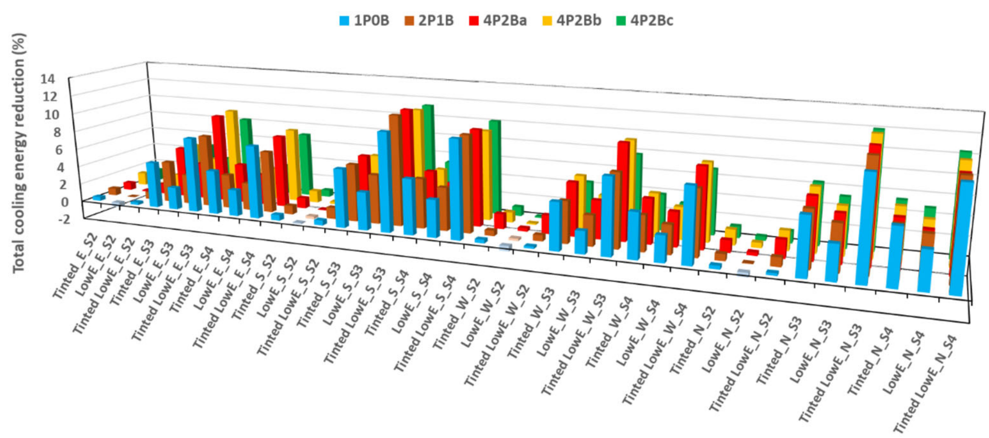

Fig. 15 Summarized cooling energy saving at different glass types, building wings and cooling scenarios

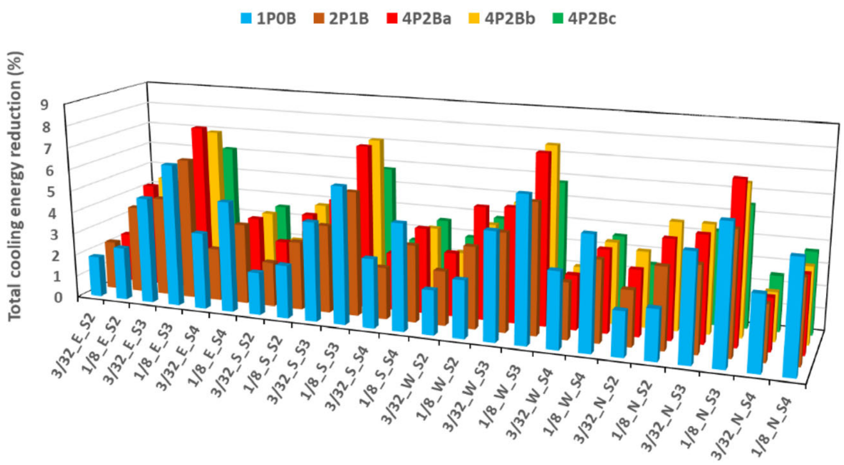

Fig. 16 Summarized cooling energy saving at different openable-window-to-floor area ratios, building wings and cooling scenarios

above the critical temperature of 29.5 °C nearly within the whole period of time including at night. Meanwhile, a temperature build-up of nearly 2 °C was found during the time when the flats were unoccupied with all the windows closed and limited ventilation.

The provision of just ventilation fans could only reduce the discomfort period to over 68% through the increase in air velocity inside the building. Compared to the sole use of air-conditioning when necessary, the optimal use of air-conditioning or fans could only lower the cooling energy demand by less than 12% at most. This was due to the short period which measured at most 26% of the total cooling time at the LDR's when the zone thermal comfort could be met solely by the operation of fans. Nevertheless, the results highlighted the strength of the proposed strategy for the precise and realistic analysis of HVAC system for use in residential buildings of subtropical regions. Parametric studies indicated that some design factors could save the total cooling energy by up to more than 12%. Further analysis could be made to investigate their potentials for heat mitigation against extreme hot weather for high-rise residential buildings.

Acknowledgements

The work described in this paper was supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (No. CU R4046-18F).

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