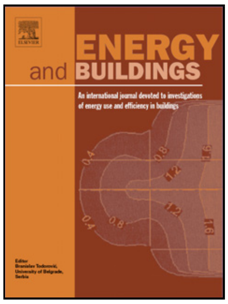

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Thermal comfort and energy performance of public rental housing under typical and near-extreme weather conditions in Hong Kong

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Highlights:

- SRY weather data is used to represent a near-extreme summer in building simulation
- Building performance of typical public rental housing types in Hong Kong is assessed
- Occupants in all building types experience a substantial duration of overheating
- Cooling energy can be saved by better passive building designs
- Findings suggest how buildings in high-density cities may cope with climate change

Abstract

Building performance evaluation is crucial for sustainable urban developments. In high-density cities, occupants suffer from poor living conditions due to building overheating, especially during increasingly frequent near-extreme summer conditions caused by climate change. To represent this situation, the summer reference year weather data was employed for building simulations using DesignBuilder. This study aims to evaluate the thermal comfort and energy consumption of four typical public rental housing (PRH) building types in Hong Kong. For free-running flats, results show generally higher air temperatures in the oldest PRH type (Slab) with a compact linear building form and the most sensitive response to outdoor temperature changes for another older PRH type (Trident) with a Y-shaped design, possibly owing to its high wall conductivity. Occupants in all building types experience a ~10% increase in the proportion of discomfort hours when compared to results for typical summer conditions, but overheating is the most severe in Slab type PRH. Following an initial assessment of the cooling energy usage, a simple sensitivity test was conducted to explore the potential energy savings by various passive design strategies, including shading and reducing the exposed cooled space. A cross-shaped building form also appears to be more energy efficient. These findings, complemented by further parametric analyses, may prove useful when designing buildings for climate change.

Keywords: indoor thermal comfort; cooling energy consumption; building simulation; summer reference year (SRY); high-density city

1. Introduction

Buildings account for around 40% of the global energy consumption, of which three quarters arise from the residential sector [1]. With growing concerns regarding environmental and health problems caused by the urban built environment, the evaluation of building performance, reflected by aspects like thermal comfort and energy use, becomes crucial for the sustainable development of cities. A common evaluation approach is to make use of commercially available simulation tools such as EnergyPlus [2]. These tools require an input of representative hourly weather data. The typical meteorological year (TMY) weather file [3] has been previously used for building energy and daylight studies in Hong Kong [4-6]. However, the TMY may be inadequate to assess the thermal performance of buildings under intensifying ‘onerous warm weather conditions’ [7], which is particularly important as evident from the excess deaths of elderly at home during the France 2003 heat wave due to poor urban and building designs [8, 9]. Therefore, to better represent such near-extreme summer conditions in building simulations, the concept of Summer Reference Year (SRY) was introduced [10]. A set of SRY weather data has also been recently derived for Hong Kong [11].

Hong Kong has a subtropical climate and is unique for its high-density high-rise urban form. In summer, overheating is common in buildings due to high air temperature, intense solar radiation, high relative humidity, and poor ventilation. This leads to thermal discomfort, a greater energy demand for mechanical cooling [12, 13], as well as a higher heat-related mortality rate [14]. The issue of overheating is critical in residential buildings, especially for comfort in bedrooms, as people have less tolerance towards high temperatures during sleep time [15]. Public rental housing (PRH) accommodates almost half of the total population in Hong Kong [16], of which most are elderly, physically disabled or financially less capable, making them even more vulnerable to extreme hot weather. To ameliorate the indoor thermal discomfort, air conditioners are extensively used to cool flats, contributing to the largest proportion of electricity consumption in the residential sector [17]; this, however, incurs high costs and may not be affordable for all. Hence, it is equally, if not more, important to evaluate the thermal comfort of buildings under free-running conditions, especially during hot and humid summers.

In face of climate change, extreme weather events, such as heat waves, are expected to become more frequent [18]. The effects are further exacerbated in dense built environments as a result of intensified urban heat island (UHI) events [19]. Consequently, occupants may turn up their air-conditioners to cool the indoor environments, which generates more exhaust heat onto the streets and raises the outdoor temperatures, leading to a vicious cycle. To enhance the livability in high-density urban environments and create the capacity for sustainable development, the Hong Kong

Government has set out a strategic plan to embrace future socio-economic and environmental challenges [20]. As one of the targets for a greener city, a 40% reduction in energy use is aimed to be achieved by 2025 [21]. With buildings accounting for 90% of the current electricity consumption in Hong Kong, it is inevitably necessary to have a significant energy cut in buildings. This should not be achieved by compromising the indoor thermal comfort of living environments, but instead, by improving building performances through better building designs.

In view of the current situation in Hong Kong as outlined above, this study aims to:

1. Assess and compare the indoor thermal comfort of four typical PRH building types in Hong Kong under free-running conditions during near-extreme summers;
2. Evaluate the climate resilience of the building types by making use of two weather datasets, namely TMY and SRY;
3. Estimate the cooling energy consumption, by air-conditioners, of the building types under near-extreme summer conditions; and
4. Explore the energy saving potentials by conducting a simple sensitivity test on passive building designs.

2. Methodology

2.1 Building types

The four PRH building types studied are namely Slab, Trident, Harmony and Concord (Figure 1). They possess distinctive building forms, different number of flats, various flat sizes, and represent different generations of PRH designs from the 1970s through to the 2000s (Table 1) [22], with Slab type PRH being the oldest, and Harmony and Concord types more prevalent amongst newer PRH estates. They are chosen to represent the typical forms of residential buildings because they are found in around 70% of all PRH estates located across Hong Kong [22]. Their floor layouts were drawn according to the Wo Che Estate, Cheung On Estate, Sheung Tak Estate and Yat Tung (I) Estate in Hong Kong respectively (Figure 1).

2.2 Building model and simulation settings

Building simulations were set up with the DesignBuilder v5 software, in which building performance data were generated using the state-of-the-art dynamic EnergyPlus v8.5 simulation engine. EnergyPlus is the official building simulation program used by the United States Department of Energy and has been extensively tested and validated by field measurements and empirical methods [23-25]. It is able to produce detailed and accurate results for building energy assessments [2, 26] and analyses of indoor natural ventilation [24, 27]. Moreover, the BESTest (Building Energy Simulation TEST) procedure, developed by the International Energy Agency to diagnose the capabilities of building energy simulation programs, has been used to verify the robustness of the DesignBuilder software [28, 29].

In DesignBuilder, models are composed of multi-zoned building blocks and component blocks. To speed up thermal calculations in large models, “adiabatic component blocks” are generally used for setting adjacent flats where internal thermal analyses are not required, whereas “standard component blocks” are used for shadings and reflection blocks. Generic models of the PRH flats were first constructed in block level and then further partitioned into zones with different activities allocated accordingly (Figure 2). Full-size windows without fitted air-conditioners or exhaust fans were assumed to have a height of 1.8m and were carefully placed based on the floor layout plans. Standard component blocks were added on top of windows where the flat above extrudes to provide shading (Figure 2a). To reduce the computational cost required, only flats of the middle floor for each building type were simulated to represent an average scenario [30, 31]; the common areas and the rest of the building were represented by a single adiabatic component block.

In order to achieve a more accurate and realistic simulation, building physical parameters, such as floor heights and cooled areas, of the modelled flats were set differently for each building type according to the reference PRH estates. Construction materials were also chosen after reviewing the literature [30, 32-34]. Details of the building model properties are presented in Table 2. Although occupants in different PRH estates may vary in household sizes and demographic backgrounds, a uniform occupant density of 0.083 people/m^2, calculated from an average living space per person of 12m^2 [16], was adopted for all four building types for a fairer comparison of the building design itself. Another parameter which plays a role in controlling the indoor thermal conditions and energy consumption is the occupancy schedule. It was set, also uniformly across the four building types, according to the survey findings of Chen and Lee [35], in which a slight difference in occupancy levels in the day during weekdays and weekends has been observed. Simulations were run using two different heating, ventilation and air conditioning (HVAC) settings separately: 24-7 calculated natural ventilation and scheduled air-conditioning (cooling only). For free-running flats, no mechanical ventilation was applied and windows were assumed to remain 30% open regardless of the outdoor weather conditions. For air-conditioned flats, cooling was applied to bedrooms and living rooms only. The cooling setpoint temperature was set to 25°C, as advised by the Hong Kong Government [36], for an overnight cooling period from 2pm to 8am [30] throughout the summer. A coefficient of power (COP) of 2.5 was adopted for the air conditioning system [37].

2.3 Weather data

Two hourly weather datasets were used in this study. They provide inputs of dry bulb air temperature, relative humidity, solar radiation, wind speed and direction etc. for realistic building simulations. The TMY represents typical year conditions based on a 25-year measured data record between 1979 and 2003, while the SRY, derived by regression analyses and applying adjustments to the Test Reference Year (TRY), represents near-extreme conditions during the extended summer months from April to September [11]. The fundamental concept of deriving the SRY is to apply regression equations and a ranking methodology to define the adjustment factors for each of the variables in the TRY dataset. The following equation shows the conceptual model for the adjustment of individual meteorological variables:

$$T_{dry(SRY)} = T_{dry(TRY)} + \Delta T_{dry} \quad (1)$$

, where $T_{dry(SRY)}$ and $T_{dry(TRY)}$ refer to the dry bulb temperatures in the SRY and TRY series and ΔT_{dry} is T_{dry} shift.

As the SRY dataset of Hong Kong has not yet been employed in building simulations, this study would serve to demonstrate how it can be used in practical applications. The responses of buildings during severely hot summers are particularly important as global climate change intensifies the effects of UHI and increases the duration and frequency of heat waves. Making use of both datasets, the indoor thermal comfort under typical and near-extreme summer conditions were compared to investigate the climate resilience of the four buildings types. For the purpose of this paper, summer is defined to be the five hottest months in a year, i.e. May to September, based on the normal meteorological conditions recorded by the Hong Kong Observatory (HKO) between 1981 and 2010 (Figure 3) [38]. Since the input data of both the TMY and SRY weather files are presented at hourly intervals, hourly data outputs for these summer months were extracted from the annual building energy simulations run in DesignBuilder for subsequent analyses of this study.

2.4 Thermal comfort analysis

The indoor thermal comfort of simulated flats were described by both air temperature and the Predicted Mean Vote (PMV) index [39]. A maximum indoor air temperature with 80% acceptability has been previously defined to be 29.5˚C for naturally ventilated buildings during hot summers in Hong Kong (Figure 4) [40]. Hours exceeding this threshold would therefore be considered overheated. Besides air temperature, factors affecting a person's thermal comfort also include mean radiant temperature, wind speed, relative humidity, as well as two personal variables of metabolic rate and clothing insulation. The PMV model uses a seven-point scale from -3 to +3 to represent human thermal sensations from too cold to too hot. In accordance with the ISO standard 7730 [41], the PMV was calculated for the simulated flats within DesignBuilder, assuming a metabolic rate of 0.9 met and a summer clothing index of 0.3 clo. The PMV generated by EnergyPlus may exceed the limits of the seven-point scale and numbers greater than 3 simply reflect extremely hot predicted sensations. The ASHRAE Standard 55-1992 [42] defines a satisfactory thermal environment as one where 90% of the occupants are thermally comfortable; this corresponds to a recommended PMV between -0.5 and +0.5 [43, 44]. Therefore, a second threshold of PMV +0.5 was adopted in this study to evaluate the number of discomfort hours in the four building types. Nevertheless, it should be noted that the PMV index has been criticised for overestimating the thermal sensation of building occupants in warm climates [45, 46], possibly due to acclimatisation of the occupants, and may limit the accuracy of the corresponding analyses.

Studies have shown that the neutral thermal sensation for people living in hot and humid climates, such as in Singapore, Bangkok, and Malaysia, often corresponds to a temperature higher than the one predicted by a traditional PMV model [47, 48]. To account for such differences, various adaptive models for thermal comfort have been proposed since the 1990s based on field and empirical studies for both free-running and air-conditioned indoor environments [49-51]. Fanger and Toftum [47] put forward an extended PMV model which introduces an expectancy factor 'e' to predict actual votes of occupants in free-running buildings in warm climates. With reference to the adjusted model, applying an expectancy factor of 0.7 yields an upper temperature limit of 29.4°C for a predicted percentage of dissatisfied (PPD) of 20 (corresponding to a PMV of around 0.85), which is highly comparable to the findings by Cheng and Ng [40] (Figure 4). With an added interest to test the suitability of the extended PMV model in Hong Kong, a third analysis of indoor thermal comfort incorporating an expectancy factor of 0.7 has been conducted to further evaluate the simulated PMVs of the four building types.

2.5 Cooling energy consumption and sensitivity test of designated parameters

To assess the energy performance of air-conditioned flats, the amount of electricity used for cooling normalised by the total volume (i.e. cooled area x height found in Table 2) of cooled space in flats, which excludes kitchens, bathrooms and balconies, was evaluated. A simple sensitivity analysis was then conducted for the building type (Trident) with the highest cooling energy consumption to explore the energy saving potentials by various passive design strategies, assuming that occupant behaviour, represented by the setpoint temperature and cooling schedule, remains the same. Design modifications include thickening the external wall to reduce the U-value, adding external overhang shading to windows, creating an indoor-outdoor space between the façade and the cooled living room, and combinations of the above. Furthermore, the building form was modified to resemble other PRH types that use less cooling energy to examine the effects due to building shapes (Figure 5).

3. Results and discussion

3.1 Indoor air temperatures under free-running conditions

The simulated indoor air temperatures of the four PRH types under free-running conditions from May to September of the SRY are presented in Table 3 and Figure 6. For most of the time, the highest and lowest temperatures are observed in Slab and Concord type PRH flats, respectively. However, the daily maximum temperature of Trident type PRH is often up to 0.5°C higher than that of Slab type PRH (Figure 6a). Trident type PRH also has the largest indoor air temperature range of 11.23°C, while Harmony type PRH has the smallest range during the whole summer period. Comparing the indoor and outdoor median air temperatures, the indoor environments are around 0.5-2°C hotter than the outdoor conditions for all four PRH types (Figure 6b); but the daily maximum indoor air temperatures generally remain below the maximum outdoor temperatures, except occasionally for Trident type PRH (Figure 6a). On the other hand, the daily minimum indoor air temperatures of all four PRH types are constantly higher than the minimum outdoor air temperatures, with a particularly large indoor-outdoor temperature difference of up to 4°C for Slab type PRH (Figure 6c). It is also worth noting that the indoor-outdoor temperature difference is often larger for relatively cooler days, e.g. during mid-June when a trough is observed in Figure 6. This may indicate that heat gain during hotter days are retained inside the buildings, hindering indoor air temperatures to fall in response to the changes in outdoor weather conditions.

3.2 Response to outdoor temperatures

To examine how the building types respond to changes in outdoor conditions, the simulated indoor air temperatures are plotted against outdoor air temperatures in Figure 7. In light of the different patterns observed for the daily maximum and minimum air temperatures (Figure 6a and c), which could be interpreted as temperatures in the day and at night, the analyses are conducted separately for daytime and nighttime temperatures. Here, daytime is defined as when the solar altitude is positive.

In agreement with the previous findings of Coley and Kershaw [52], the relationship between indoor and outdoor temperature changes is linear. The responses are generally more sensitive during nighttime, as represented by a steeper gradient, for all four PRH types. Slab type PRH is the least responsive to outdoor temperature changes. Heat trapped from solar radiation in the day may hinder the indoor air temperatures from lowering at night, causing the daily minimum temperatures of Slab type PRH to remain much higher than outdoor temperatures. Trident type PRH shows the most sensitive response during both daytime and nighttime, meaning that it follows the most closely to the changes in outdoor temperatures. This explains the large temperature range and high daily maximum temperature observed for Trident type PRH. A notable feature in the building design of Trident type PRH is its thin external wall, and thus high U-value of 3.33 $Wm^{-2}K^{-1}$ (Table 2). It is therefore reasonable to assume that more conductive walls cause a quicker heat gain from outdoors, and consequently warming up the indoor air to cause higher maximum temperatures. There have also been studies that suggest higher risks of overheating in British dwellings with poorer insulation and greater U-values during hot spells [53, 54]. However, by repeating the simulation for Trident type PRH with a reduced U-value, it is found that this is not the only factor causing the sensitive response of Trident type PRH (results not shown), and thus points to the need for a more detailed parametric analysis to examine other potential governing factors, such as the window-to-wall ratio and the thermal mass of walls.

3.3 Thermal comfort under free-running conditions

3.3.1 Indoor air temperature

The thermal comfort in the four PRH types are first described by air temperature. The durations of discomfort felt by occupants during daytime and nighttime in the four building types are shown by the number of hours with indoor air temperatures above the 29.5°C threshold with 80% acceptability (Figures 8a and c), whereas the intensity of discomfort during such hours are shown by the corresponding temperature distributions (Figure 9). Looking first at the example period from late August to mid-September (Figure 6b), median indoor air temperatures often exceed the comfort threshold even when outdoor temperatures do not. Overheating is observed in all four PRH types, but with different durations and intensities. Occupants in Slab type PRH experience the most hours of discomfort during both daytime and nighttime. During near-extreme summer conditions, the median indoor air temperature of Slab type PRH is 29.71°C (Table 3), implying that the building is overheated for more than half of the time in summer. For Trident type PRH, occupants experience overheating during more than 50% of the time in the day and more than 40% of the time at night. Harmony and Concord types PRH show largely similar trends with around 40% and 30% of the summer days and nights above the air temperature threshold. Referring to Figure 9a, it is clear that occupants in Slab and Trident types PRH experience both longer durations and higher intensities of discomfort than those in Harmony and Concord types PRH in the day. The situation is similar at night (Figure 9b), but Slab type PRH stands out with a worse thermal comfort condition.

3.3.2 Standard PMV model

The second measure of thermal comfort in the four PRH types makes use of the standard PMV index, which, besides air temperature, takes into account other parameters of thermal comfort, such as the radiant and convective heat transfers [39, 41, 55]. Since a PMV of +0.5 corresponds to a 90% acceptability of indoor thermal comfort (instead of 80%), results show significantly more hours of discomfort for the occupants in all four building types compared to the earlier analysis using the air temperature threshold (Figures 10a and c). Nevertheless, the comparison between building types is largely similar. Occupants in Slab type PRH flats experience the most hours of discomfort, followed by those living in Trident, and then Harmony and Concord types PRH flats. During nighttime, results show that Harmony type PRH has a higher number of discomfort hours than Concord type PRH. Referring to the distribution of PMV (Figure 11), the distribution patterns for Slab and Trident types PRH are clearly shifted towards the higher end of the PMV scale compared to that for Harmony and Concord types PRH, indicating that occupants experience more time with a warmer thermal sensation. Occupants of Trident type PRH even experience some extremely hot predicted sensations (PMV above +3) during both daytime and nighttime.

Although the PMV index may be a more representative and internationally accepted approach to assess thermal comfort of the building types compared to the measure solely on air temperature, it has not been adapted to the local conditions of Hong Kong and may overestimate the thermal sensation of occupants. Therefore, this analysis is presented separately from the one using the local air temperature threshold, with the aim to provide a more comprehensive description of the thermal comfort conditions of PRH flats in Hong Kong.

3.3.3 Adjusted PMV model

Using an adjusted PMV model which incorporates an expectancy factor ‘e’ of 0.7, the corresponding distributions of PMV of the discomfort hours for the four building types are shown in Figure 12. Since occupants of non-air-conditioned building in warm climates often find relatively high temperatures more tolerable than the standard PMV model predicts [47], the intensities of discomfort felt by occupants under near-extreme summer conditions are generally less severe according to the adjusted PMV model. No PMV values are found beyond 2.5 for all four building types. The distribution patterns for each building type remain similar to that shown in Figure 11, except that the peaks in the distribution of discomfort hours for Slab and Trident types PRH flats are now observed between a PMV of 1-1.5 (rather than 1.5-2), while the peaks for Harmony and Concord types PRH flats fall between a PMV of 0.5-1 (rather than 1-1.5).

With an interest to examine whether the adjusted PMV model can suitably describe the thermal discomfort of occupants in Hong Kong PRH flats under near-extreme summer conditions, the number of discomfort hours determined from the analyses using the 29.5°C air temperature threshold and an adjusted PMV threshold of 0.85 are plotted together in Figure 13. Both thresholds represent an acceptability of 80%. It is worth noting that when using the adjusted PMV model, which takes into account parameters other than air temperature, Slab and Trident types PRH flats display a worse situation of discomfort, especially at night. On the other hand, thermal conditions in Harmony and Concord types PRH flats may be more acceptable than expected in the day for occupants when parameters other than air temperature are considered. Moreover, when the adjusted PMV model is used, Concord type PRH perform slightly better than Harmony type PRH with respect to the amount of time when occupants feel too warm. Although the various durations of thermal discomfort felt by occupants in the different types of PRH are largely comparable in terms of the general trend among the building types, it is acknowledged that simulation and model results would need to be verified using field survey data in order to assess the appropriateness of the adjusted PMV model for non-air-conditioned indoor environments in Hong Kong.

3.4 Comparison between TMY and SRY

The number of discomfort hours during typical and near-extreme summer conditions are plotted side-by-side in Figures 8 and 10. The increase in the proportion of discomfort hours are also shown for each PRH type. This could potentially be a measure of climate resilience for the different building types. Based on indoor air temperatures only, the increase in discomfort hours is around 10% for all four PRH types. Trident type PRH shows the smallest increase in the number of discomfort hours during the day, while Concord type PRH shows the smallest increase in the number of discomfort hours during the night. On the other hand, Concord type PRH shows a slightly larger increase in the number of discomfort hours during the day, while Slab type PRH shows the largest increase in the number of discomfort hours during the night. When the PMV index is considered, the difference in the duration of discomfort between typical and near-extreme summer conditions becomes less evident for Slab and Trident types PRH. However, there is an obvious 8-10% increase in the proportion of time where occupants experience thermal discomfort for Harmony and Concord types PRH. The increase is particularly evident for Concord type PRH in the day. After careful examination of the simulation results, the reason for the small increase in discomfort hours for Slab and Trident types PRH is found to be due to their already poor performance in typical summer conditions, and not their abilities to resist climate change. Considering that their relatively small percentage increases do not imply better thermal comfort under near-extreme conditions, it may therefore not be a fair and effective way to evaluate the climate resilience of the building types by looking at the increase of discomfort hours over a certain threshold.

3.5 Cooling energy consumption

To cope with the high indoor air temperature and poor thermal comfort conditions as described in earlier sections, air conditioning is commonly used to cool the indoor environment during summer in Hong Kong. The amount of electricity consumed for cooling in summer, normalised by the cooled volume of flats, of the four PRH types is presented in Figure 14. With air conditioners operating in the living rooms and bedrooms as specified by the cooling schedule, the indoor thermal comfort conditions are significantly improved. Taking Trident type PRH as an example, the average PMV for all the simulated flats in summer dropped from +1.2 to +0.09, which is very close to a neutral thermal sensation. This proves that the setpoint temperature and cooling schedule have been set reasonably. Trident type PRH is found to have the highest total summer cooling load of around 20kWh/m^3, Concord type PRH has the second highest consumption of 18.7kWh/m^3, and Harmony consumes 17.9kWh/m^3 of energy for summer cooling. Although Slab type PRH is generally the hottest under free-running conditions, it requires only 16.8kWh/m^3 to maintain the same indoor temperature by mechanical cooling. In search of the explanation for this interesting observation, a positive correlation is found between the proportion of exposed cooled space and cooling energy consumption. A noticeable feature of a Slab type PRH flat is the setback of its living from the façade, resulting in an isolated cooled space from the outdoors (Figure 15). A balcony serves as an indoor-outdoor space to modulate the indoor conditions of the living room and maintain a stable indoor temperature. Hence, this may explain the lower cooling energy demand for Slab type PRH flats.

3.6 Energy saving potential for Trident type PRH

Apart from the setback of the cooled space from the façade, other building design features may also affect the cooling energy demand. This section looks into the potential energy savings of various passive design strategies on Trident type PRH, which currently has the highest energy consumption. The modifications to the design are detailed in Table 4 and the results are shown in Figure 16. Also plotted is the 40% energy reduction target set by the Hong Kong government for the year 2025 as a reference.

All simulations with modifications applied show a reduction in cooling energy consumption. However, none is able to achieve an energy saving close to the 40% target. The energy consumption of Trident type PRH with a modified U-value is still higher than that of Harmony type PRH, indicating the difference in external wall U-value is not the only reason for the difference in cooling energy demand. By adding shading devices to windows, high angle solar radiation during midday is shaded from the indoor environment. As a result, energy consumption decreases by 4.6%. Since creating an unconditioned space between the façade with the largest window and the living room is not able to completely isolate the cooled space from the outdoors, this design strategy is not as effective as the setback in Slab type PRH flats. Combinations of two of the above three modifications give approximately a doubled energy saving potential, but applying all three modifications do not result in a tripled effect. This suggests that in real-life situations where more modifications require more resources and higher costs, it may not be cost-effective to incorporate all the available modifications. Instead, combinations of the most effective passive design strategies, not restricted to the ones examined in this study, should be chosen.

Three distinct building forms are represented by the four typical PRH building types studied – linear, Y-shaped and cross-shaped. As seen from the thermal comfort analysis of the buildings under free-running conditions, the cross-shaped PRH types Harmony and Concord yield similar indoor air temperatures, suggesting a potential correlation between building shape and its performance. To investigate the effect of building shapes to building energy usage, Trident type PRH flats are rearranged in linear and cross-shaped forms (Figure 5). A linear arrangement with the flats facing north and south gives a small reduction in cooling energy consumption, while a substantial 18% of cooling energy is saved when flats are arranged in a cross-shape. This may be attributable to the self-shading effect by the extended building blocks in a cross-shape. Although it is not possible to rearrange flats in existing building as it has been done in the model, these results may inform architects or engineers about which building forms are more energy efficient. Furthermore, this simple sensitivity test suggests that it is difficult to achieve the target set by the

Hong Kong government solely depending on passive building design strategies for high-density residential buildings. Therefore, improvements on the active HVAC systems of buildings and changes in human behaviour, such as the habit of turning on air conditioners overnight, are also necessary to complement the energy savings due to better building designs.

3.7 Implications on building design

Although this research is based on a case study in Hong Kong, the application of its findings are not restricted by location. Studies have long suggested the merits of high-density and compact cities for sustainability [56, 57]. More than half of the global population currently live in cities and the proportion of urban dwellers will continue to grow rapidly in the next few decades, especially in developing countries [58]. In order to cater for the massive urban population, the world is moving irreversibly towards the need for high-density cities like Hong Kong. However, the process of urbanisation is often accompanied by an increase in energy consumption [59, 60]. Moreover, climate change exerts extra stress on cities in forms of intensified UHIs, more frequent heat waves, and exacerbated air pollution [61, 62]. Therefore, it is imperative to build climate resilient cities with thermally comfortable and energy efficient buildings to cope with these global challenges. With an understanding on how building designs, including the building physical parameters, interior designs of flats and shapes of building blocks, influence the building energy performance, the same principles can be applied for future urban developments in Hong Kong, the greater Pearl River Delta, or possibly other cities with similar hot and humid climates around the world. Taking this study as a starting point, a further parametric study should be conducted with the aim to generalise the research findings for improving the design of buildings in high-density high-rise environments.

4. Conclusion

In this building simulation study, the indoor thermal comfort and energy performance of four typical PRH building types under typical and near-extreme summer conditions in Hong Kong have been evaluated. Under free-running conditions, the older Slab and Trident types PRH are found to be generally hotter than Harmony and Concord types PRH. A more sensitive response of Trident type PRH to changes in outdoor temperatures give rise to its high daily maximum air temperatures and large temperature range for the whole summer. During near-extreme summer conditions, occupants of all four PRH types experience thermal discomfort for a substantial proportion of the time, but the durations and intensities of discomfort vary for each building type. Occupants in Slab type PRH suffer the most, with indoor conditions exceeding acceptable comfort thresholds for more than 50% of the time, both during daytime and nighttime. On the other hand, Concord type PRH has the least number of discomfort hours. Results generally agree for the analyses using a local temperature threshold and an adjusted PMV model for free-running buildings in warm climates. All four building types show an approximately 10% increase in the proportion of discomfort hours when weather conditions change from typical to near-extreme. Although comparing the results from simulations using the TMY and SRY weather files may give an idea of how well the buildings are able to cope with climate change, such a comparison alone is insufficient to evaluate the climate resilience of buildings.

Air conditioning is a common way to mitigate the high indoor temperatures in PRH flats during summer in Hong Kong. Results show that Trident type PRH has the highest cooling energy consumption, while Slab type PRH, which is the hottest under free-running conditions, requires the least amount of energy for cooling. This may be explained by its building design, which features an isolation of its cooled space from the outdoors. To explore how passive building designs may have an impact on building energy performance, a simple sensitivity test has been conducted for Trident type PRH. Decreasing the external wall U-value, adding shading devices, and setting back the cooled space from the façade are all able to reduce the cooling energy consumption of the flats. Besides, a cross-shaped building form appears to be the most energy efficient. However, to achieve the 40% energy reduction target set by the Hong Kong government, better passive building designs must be complemented by other methods to save energy, such as improvements on the active HVAC systems and changes in human behaviours.

This study is the first to employ the newly developed SRY weather data in building energy simulations. The findings provide examples of information that may be useful for improving building designs in high-density urban environments under climate change, but are by no means exhaustive in terms of the practical applications of the SRY dataset. Certain limitations on the accuracy of the thermal comfort analyses have been acknowledged. Results could also be compared with real measurements during episodes of heat waves to validate the simulated outcomes. To further the scope of this study, other elements of thermal comfort, such as mean radiant temperatures, relative humidity and indoor air speeds, should be considered. EnergyPlus simulations could even be coupled with computational fluid dynamics models to evaluate the indoor air movements provided by natural ventilation, which is particularly important in hot and humid climates. In addition, more detailed and comprehensive parametric studies on both passive and active design strategies would be useful to formulate guidelines for climate resilient building designs that provide better thermal comfort in the future.

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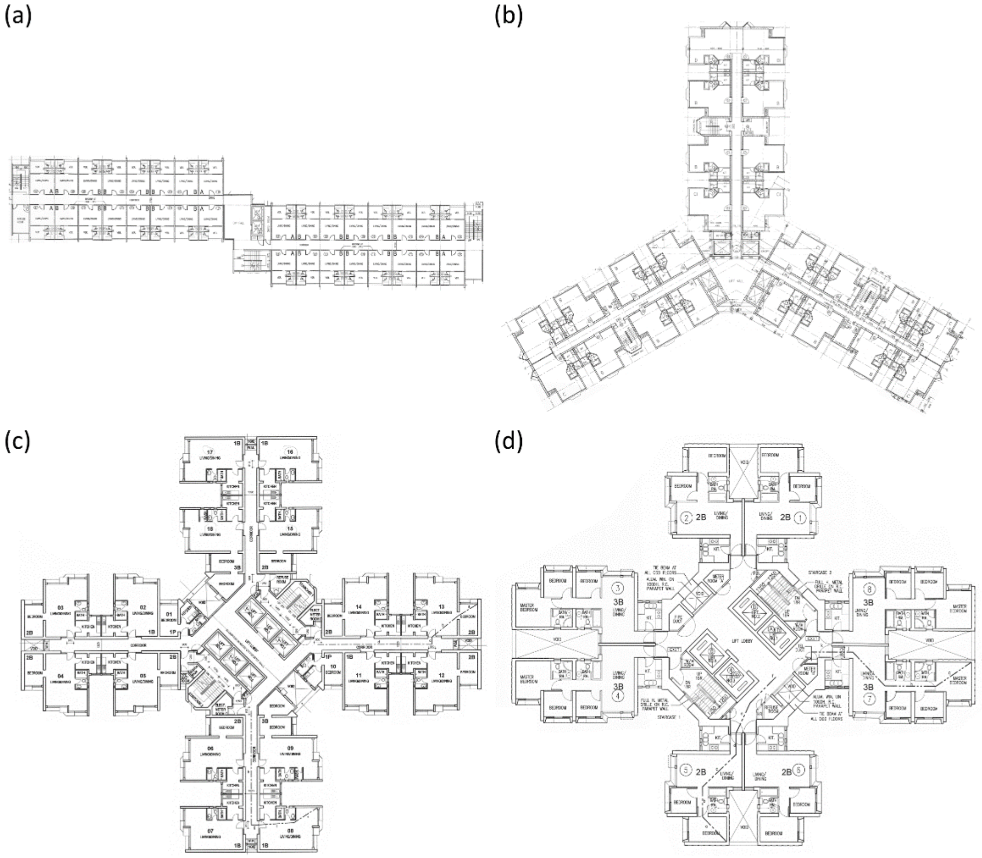


Figure 1 Layout plans of the (a) Slab, (b) Trident, (c) Harmony and (d) Concord type PRH in Hong Kong (plans are not drawn to the same scale).

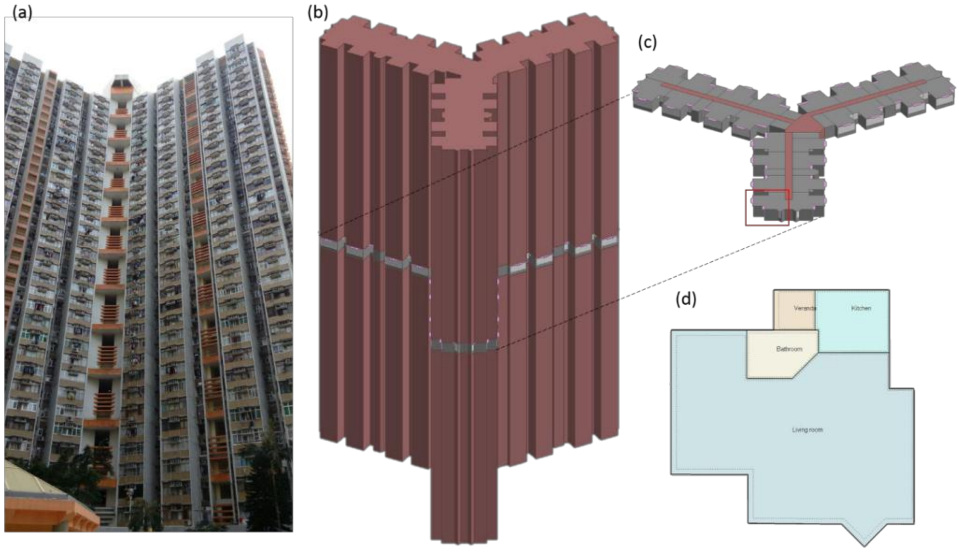


Figure 2 (a) On Chiu House (Trident type) in Cheung On Estate and generic models of (b) the whole building, (b) mid-floor flats and (c) a partitioned flat constructed in DesignBuilder.

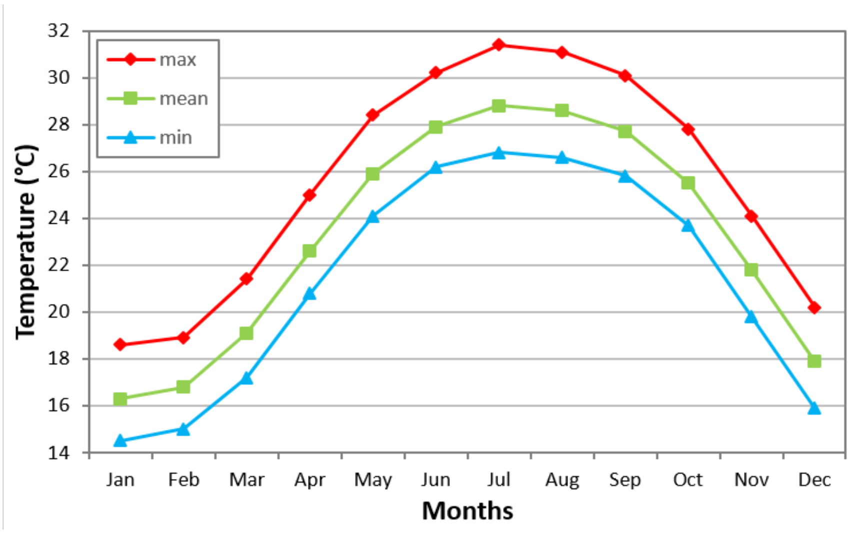
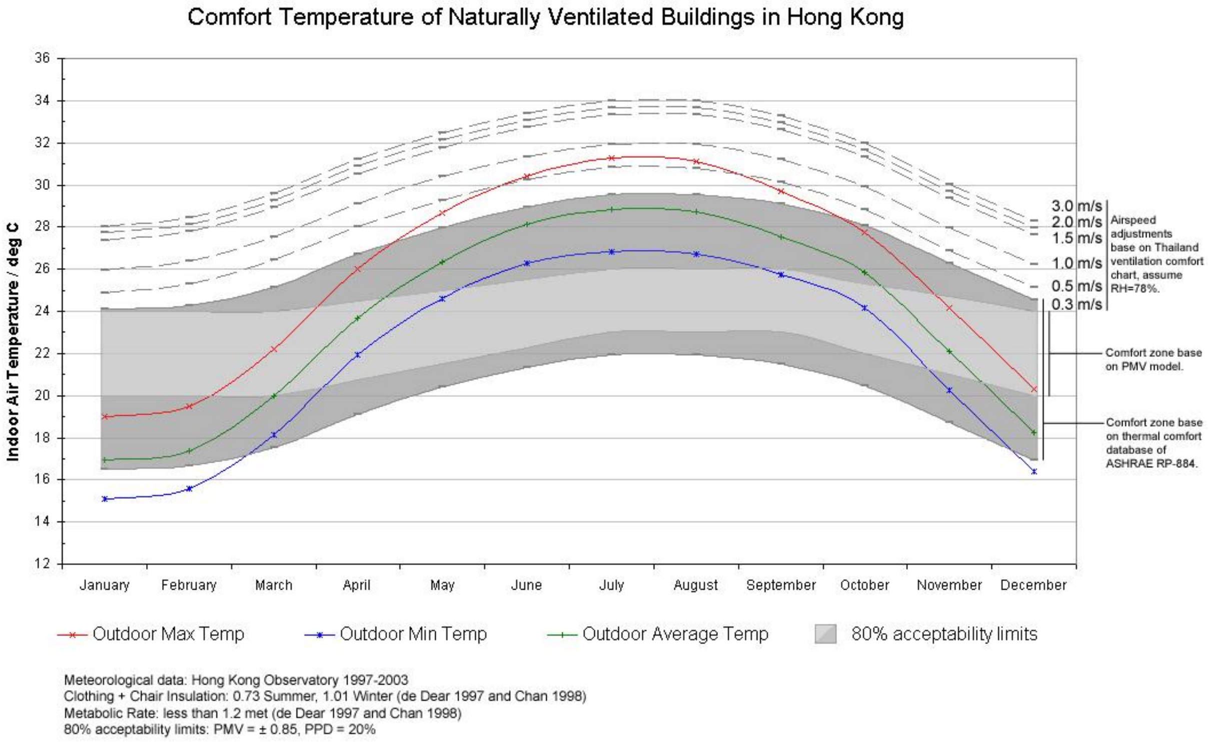


Figure 3 *Monthly means of daily maximum, mean and minimum temperature recorded at the Hong Kong Observatory between 1981 and 2010*.


Comfort Temperature of Naturally Ventilated Buildings in Hong Kong

Meteorological data: Hong Kong Observatory 1997-2003
Clothing + Chair Insulation: 0.73 Summer, 1.01 Winter (de Dear 1997 and Chan 1998)
Metabolic Rate: less than 1.2 met (de Dear 1997 and Chan 1998)
80% acceptability limits: PMV = ± 0.85, PPD = 20%

Figure 4 *Comfort temperature chart for naturally ventilated buildings in Hong Kong (used with permission from Cheng and Ng [40]).*

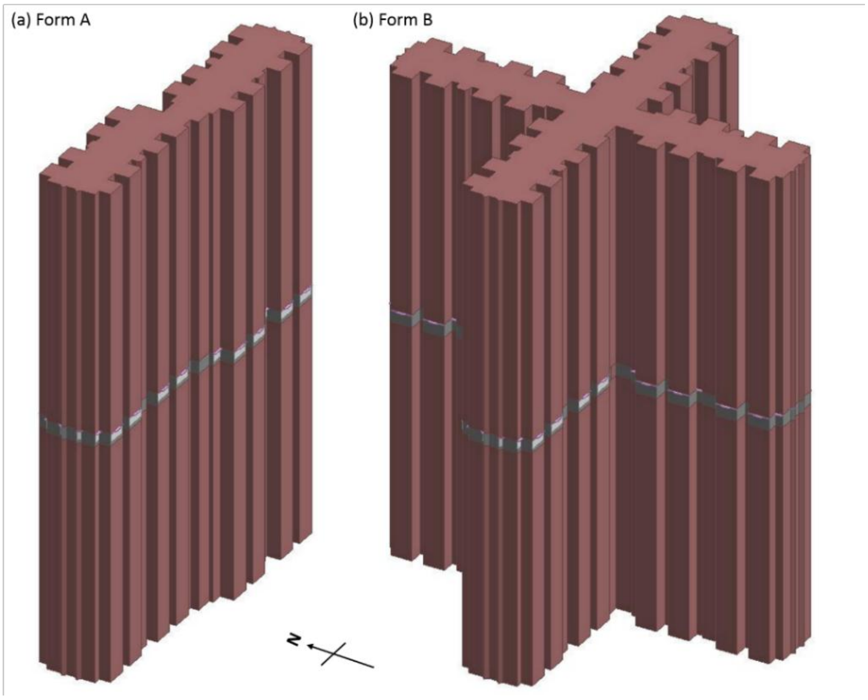
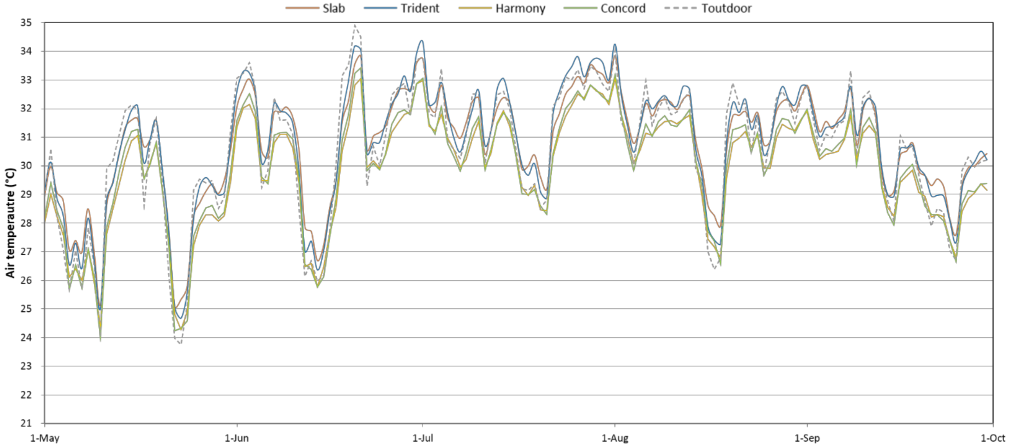
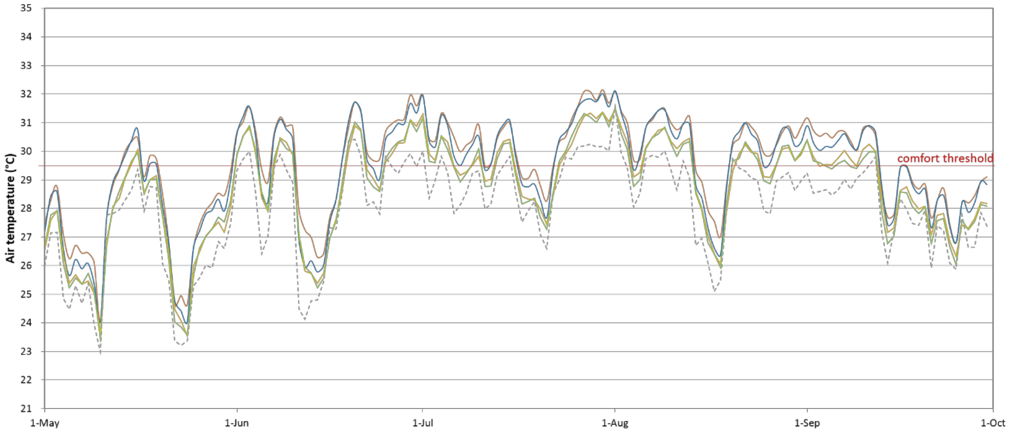


__Figure 5__ Models of the Trident PRH flats with modified building forms (a) A, resembling Slab and (b) B, resembling Harmony or Concord building types.

(a) Maximum



(b) Median



(c) Minimum

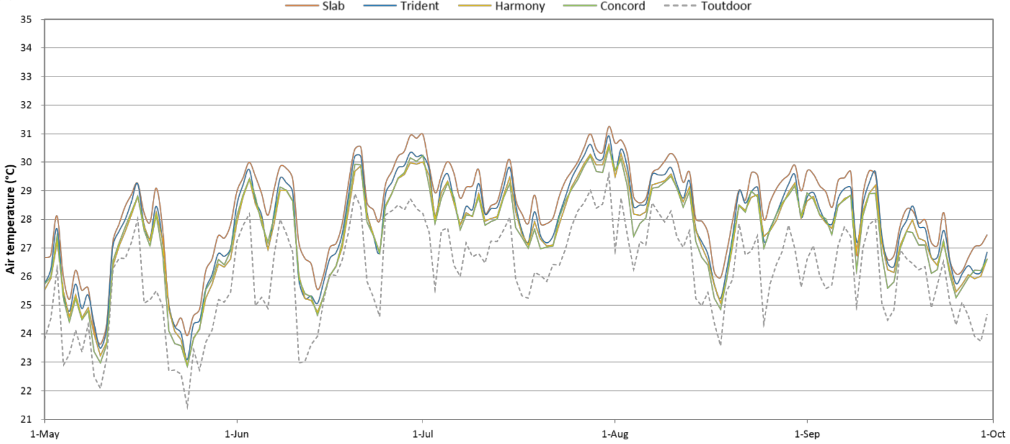
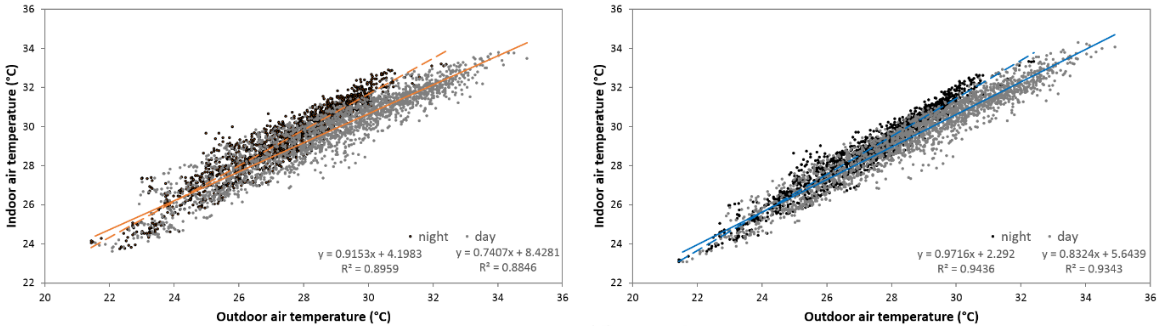
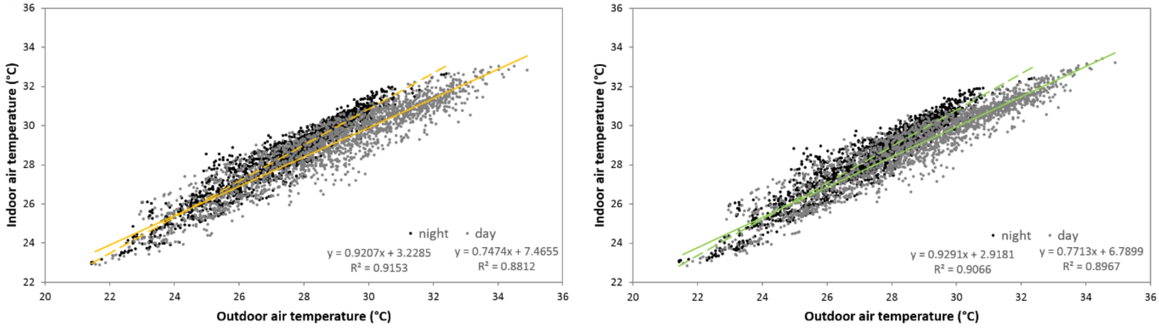


Figure 6 *(a) Maximum, (b) median, and (c) minimum outdoor air temperatures and simulated indoor air temperatures of the four PRH types under free-running conditions during near-extreme summer conditions, as represented by the SRY weather dataset. Indoor air temperatures presented have been averaged over all simulated flats. The 29.5°C maximum acceptable indoor air temperature for thermal comfort is marked in red in (b) for reference.*



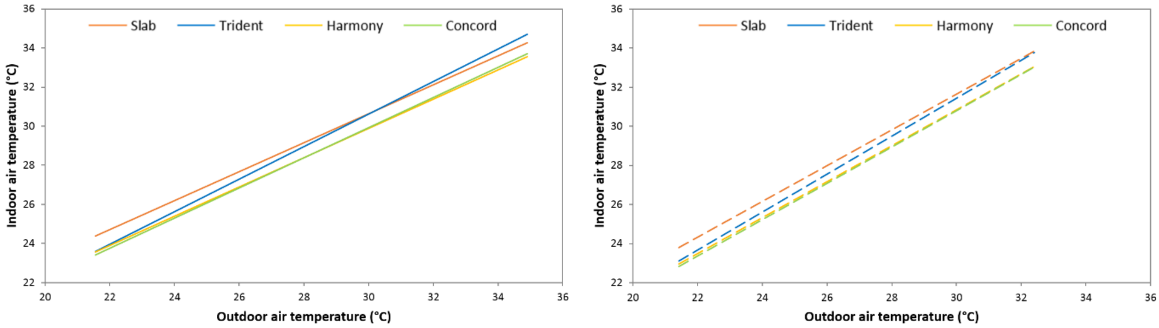
(a) Slab

(b) Trident



(c) Harmony

(d) Concord



(e) Daytime

(f) Nighttime

Figure 7 *Simulated indoor air temperatures against outdoor air temperatures for (a) Slab, (b) Trident, (c) Harmony, and (d) Concord types PRH. Comparisons of the responses of buildings to outdoor temperature changes during (e) daytime and (f) nighttime (dashed lines).*

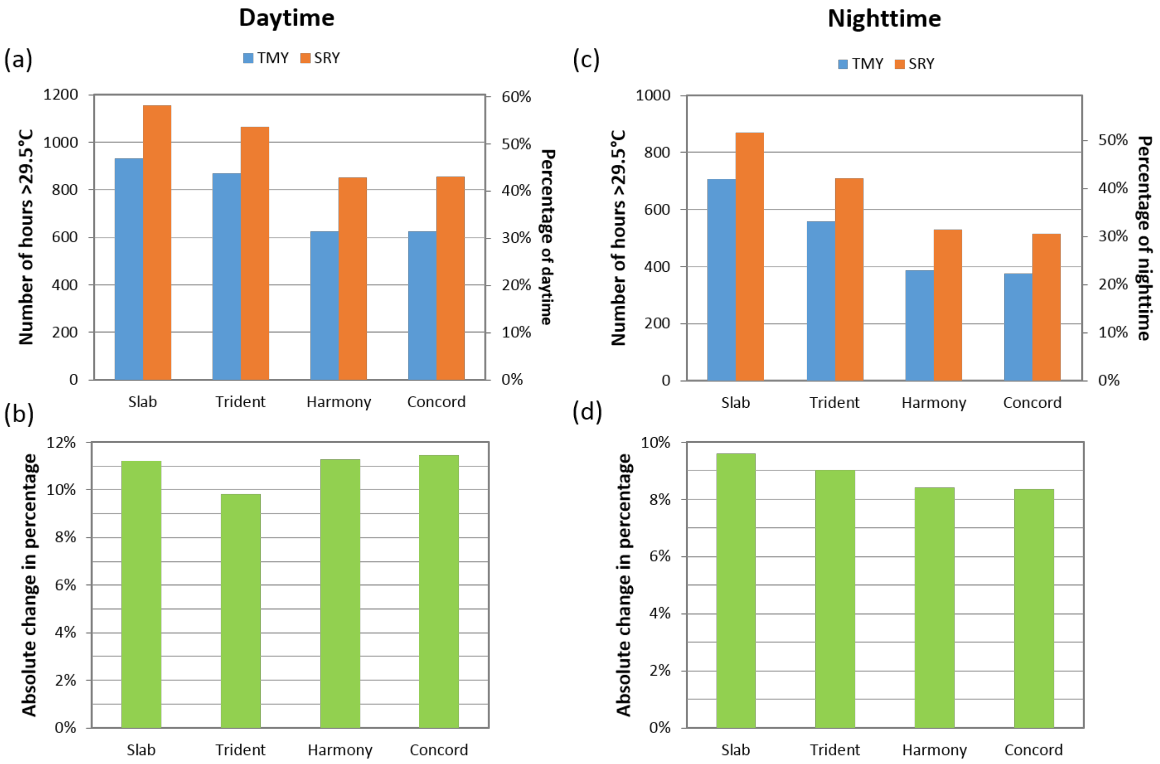


Figure 8 Durations of thermal discomfort in the four PRH types, using the air temperature threshold of 29.5°C, and the comparison between typical and near-extreme summer conditions during (a,b) daytime and (c,d) nighttime.

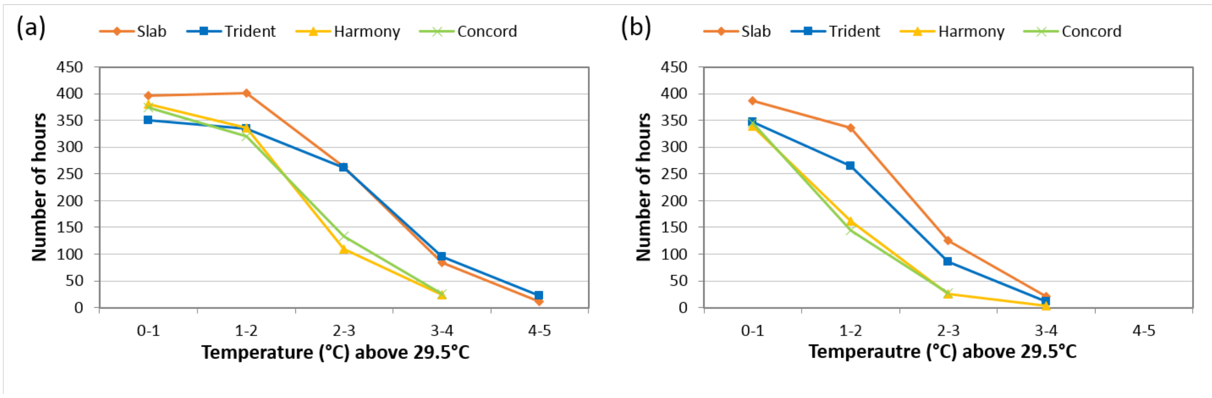


Figure 9 Temperature distribution of the discomfort hours for the four PRH types during (a) daytime and (b) nighttime under near-extreme summer conditions.

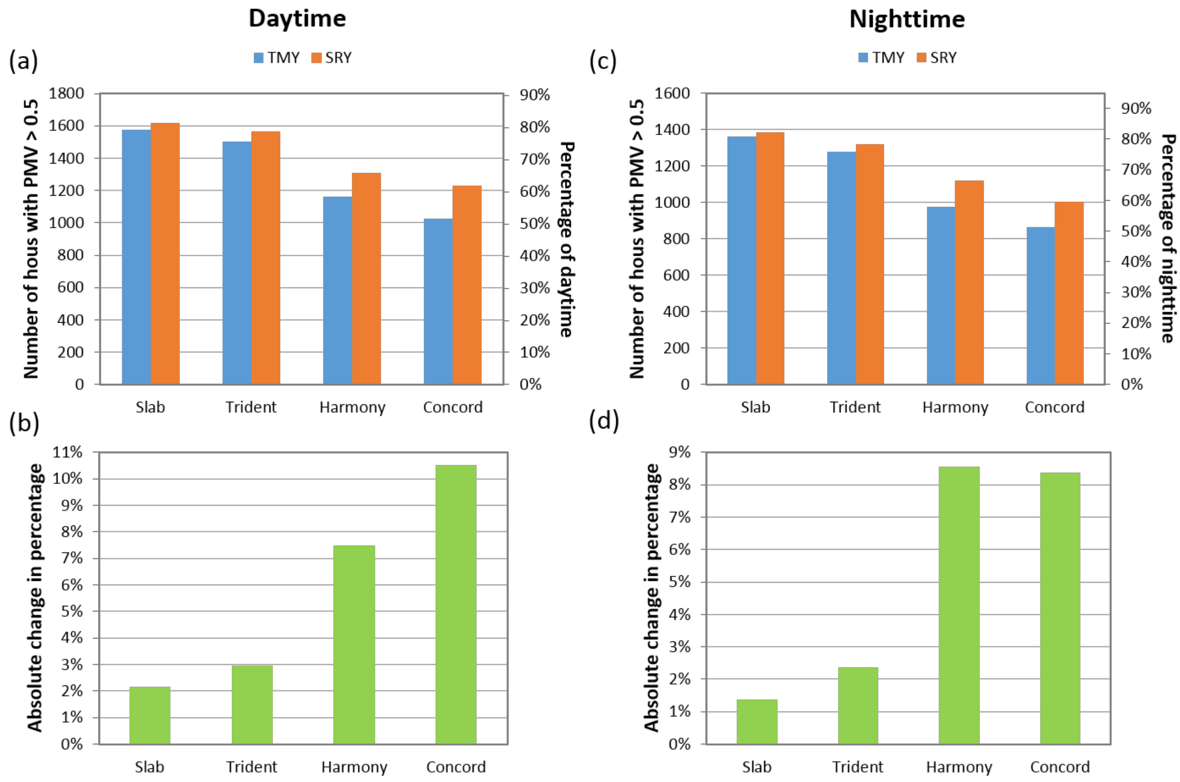


Figure 10 *Durations of thermal discomfort in the four PRH types, using the PMV threshold of +0.5, and the comparison between typical and near-extreme summer conditions during (a,b) daytime and (c,d) nighttime.*

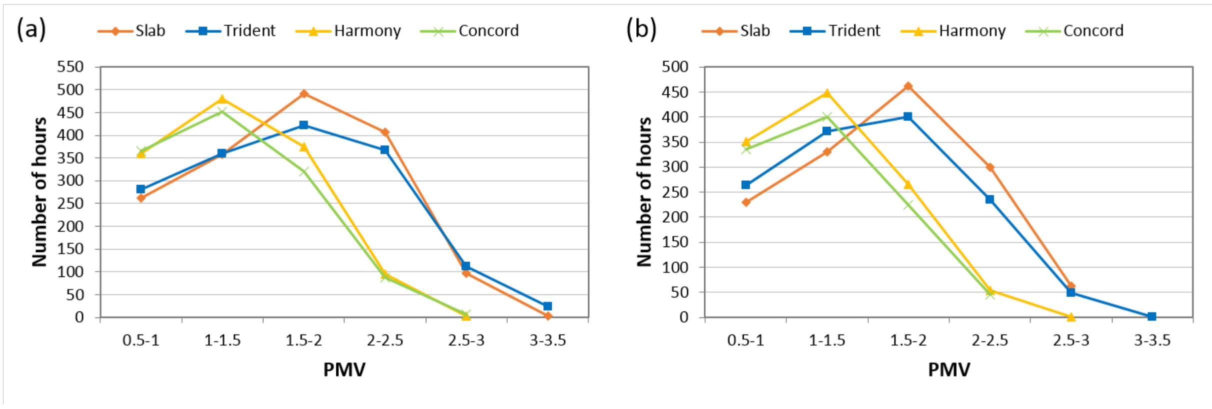


Figure 11 *PMV distribution of the discomfort hours for the four PRH types during (a) daytime and (b) nighttime under near-extreme summer conditions.*

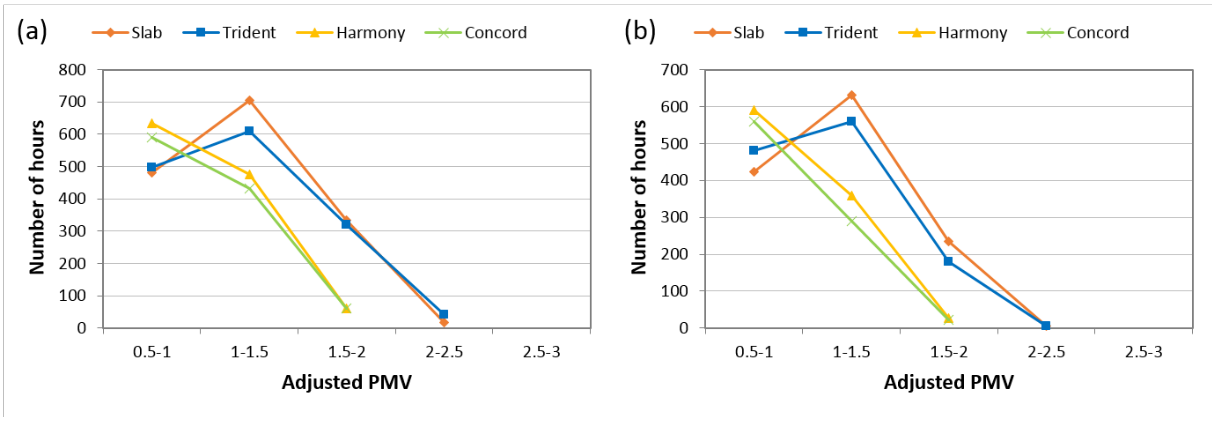


Figure 12 *Adjusted PMV (e = 0.7) distribution of the discomfort hours for the four PRH types during (a) daytime and (b) nighttime under near-extreme summer conditions.*

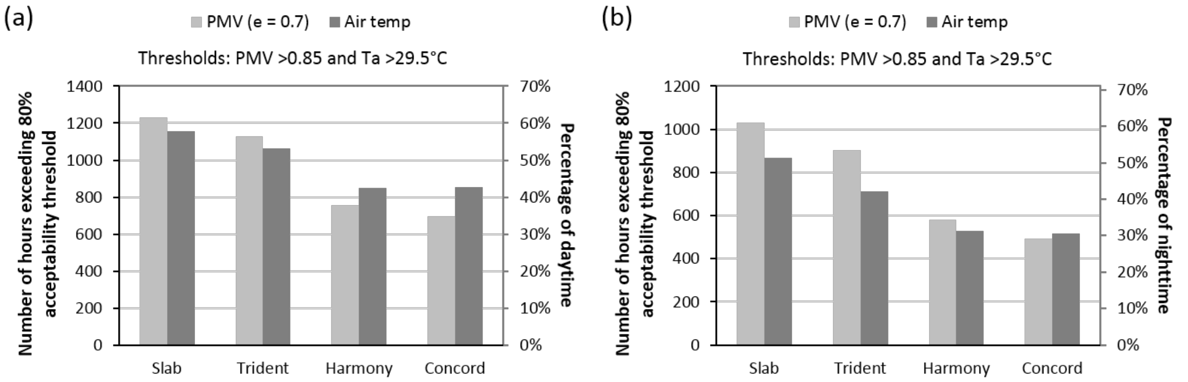


Figure 13 *Comparison of the durations of thermal discomfort in the four PRH types when using the air temperature threshold of 29.5°C and an adjusted PMV (e = 0.7) threshold of 0.85, under near-extreme summer conditions.*

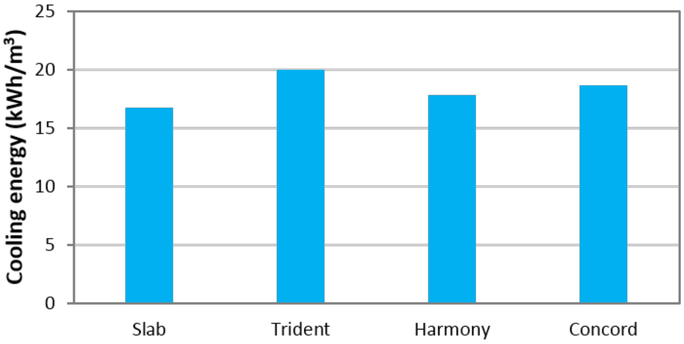


Figure 14 *Total normalised cooling energy consumption of the four PRH types during near-extreme summer conditions.*

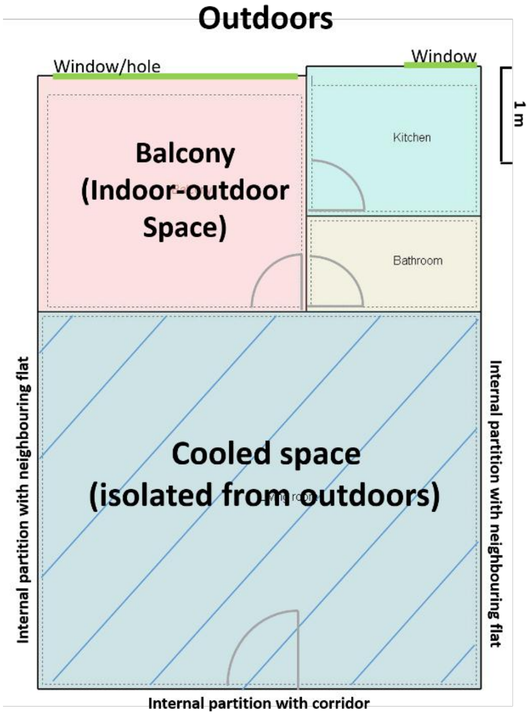


Figure 15 *Layout plan of a Slab type PRH flat with an isolated cooled space.*

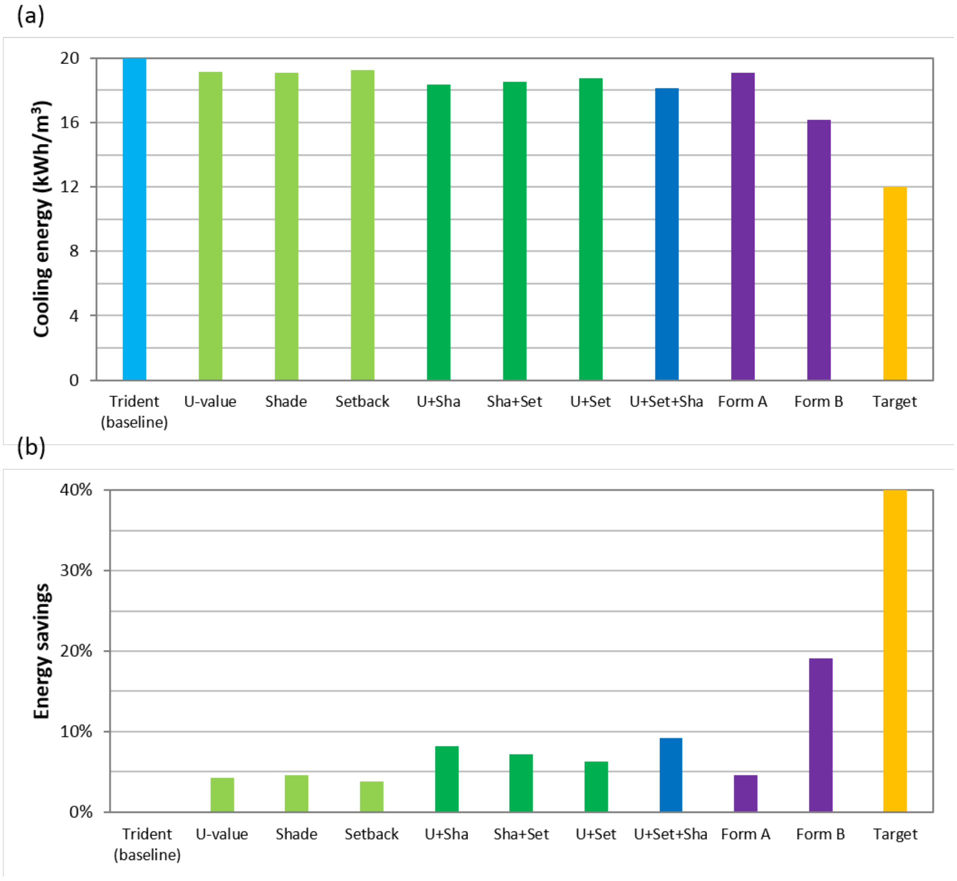


Figure 16 *(a) Normalised cooling energy consumption and (b) potential energy savings when various design strategies are applied.*

***Table 1** General information of the four typical PRH building types and reference estates in Hong Kong*.

Building Type	**Slab**	**Trident**	**Harmony**	**Concord**
Reference PRH estate	Wo Che Estate	Cheung On Estate	Sheung Tak Estate	Yat Tung (I) Estate
Year of intake	1977	1988	1998	2001
No. of storeys	13	35	42	40
No. of flats per storey	32	24	18	8
Flat sizes (m^2)	26.8 – 28.0	31.9 – 44.3	16.0 – 50.8	35.3 – 45.9

Table 2 *Building physical parameters, construction materials and their properties used in the simulations.*

	Slab	**Trident**	**Harmony**	**Concord**
Building physical parameters				
Floor height (m)	2.6	2.7	2.7	2.75
Total occupied floor area (m^2)	842.5	920.6	670.5	325.1
Cooled area (i.e. living room, bedroom) (m^2)	555.4	731.2	506.2	256.8
Window/hole to external wall ratio	0.304	0.305	0.167	0.148
Building construction				
External wall (outside to inside)				
U-value (W m^{-2} K^{-1})	3.13	3.33	2.88	2.75
- Mosaic Tile (mm)	5			
- Concrete Gypsum Plasterboard (mm)	10			
- Concrete (mm)	175	135	235	272
- Gypsum Plastering (mm)	13			
Roof				
U-value (W m^{-2} K^{-1})	0.58			
- Asphalt Mastic Roofing (mm)	20			
- Expanded Polystyrene (mm)	50			
- Reinforced Concrete (mm)	200			
- Gypsum Plasterboard (mm)	13			
Internal partition				
U-value (W m^{-2} K^{-1})	2.86			
- Gypsum Plaster (mm)	10			
- Concrete (mm)	80			
- Gypsum Plaster (mm)	10			
Floor slab				
U-value (W m^{-2} K^{-1})	2.48			
- Floor Tiles (mm)	10			
- Reinforced Concrete (mm)	180			
- Gypsum Plasterboard (mm)	10			
Glazing				
U-value (W m^{-2} K^{-1})	5.75			
- Clear Float Glass (mm)	6			

Table 3 *Summary of the outdoor and simulated indoor air temperatures and temperature ranges of the four PRH building types. The highest temperature/largest range is highlighted in red, the lowest temperature/smallest range is highlighted in blue.*

Air temperature (°C)	**Outdoor**	**Slab**	**Trident**	**Harmony**	**Concord**
Maximum	34.90	33.81	34.32	33.04	33.42
Quartile 3	29.63	30.90	30.73	30.15	30.11
Medium	28.20	29.71	29.41	28.92	28.89
Quartile 1	26.53	28.26	27.90	27.45	27.42
Minimum	21.43	23.63	23.09	22.88	22.85
Range	**13.47**	**10.18**	**11.23**	**10.16**	**10.57**

Table 4 *Detailed explanation of the modifications applied to Trident type PRH for the sensitivity test.*

Modification	**Explanation**
U-value	The external wall U-value of is reduced from 3.33 $Wm^{-2}K^{-1}$ to 2.88 $Wm^{-2}K^{-1}$, which is the same as Harmony type PRH.
Shade	1m overhang shading devices are added on top of all windows.
Setback	An internal partition, with a 0.6m wide door (same as the balcony of Slab type PRH), is added approx. 2.4m from the façade with the largest window in the living room.
U+Sha	A combination of ‘U-value’ and ‘shading’ is applied.
Sha+Set	A combination of ‘shading’ and ‘setback’ is applied.
U+Set	A combination of ‘U-value’ and ‘setback’ is applied.
U+Set+Sha	A combination of ‘U-value’, ‘setback’ and ‘shading’ is applied.
Form A	Trident PRH flats are arranged in a building form that resembles Slab type PRH (Figure 5a)
Form B	Trident PRH flats are arranged in a building form that resembles Harmony or Concord type PRH (Figure 5b)