Energy & Buildings 228 (2020) 110469

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enb

Effectiveness of passive design strategies in responding to future climate change for residential buildings in hot and humid Hong Kong

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ARTICLE INFO

Article history:
Received 23 March 2020
Revised 22 July 2020
Accepted 7 September 2020
Available online 20 September 2020

Keywords:
Climate change
Passive design
Building energy simulation
Sensitivity analysis
Adaptive thermal comfort

ABSTRACT

The application of passive design strategies is crucial at the early architectural design stage for building energy use minimization. However, the time-varying effectiveness of passive design strategies in responding to future climate change in hot and humid climates are rather limited in the literature. This paper aims to examine the dynamic effectiveness of passive design strategies for residential buildings in Hong Kong under the context of future climate change. Using the newly developed hourly weather data and adaptive comfort standard model, the dynamic effectiveness of viable passive design strategies for residential buildings are evaluated over time in the 21st century by plotting Givoni building bioclimatic charts (BBCC) and simulation-based sensitivity analyses in a validated EnergyPlus model. Results show that solar protection strategies are still the highly sensitive strategies for building energy performance and the effectiveness of external windows' airtightness is expected to increase up to 329% by the end of this century, whereas the cooling potential of ventilation utilization will significantly decrease over time. When the different combination of sensitive passive design parameters is implemented onto the baseline residential building model for different climate scenarios, the annual and peak cooling load can be reduced up to 56.7% and 64.5%, respectively.

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1. Introduction

1.1. Background of study

According to the International Panel on Climate Change (IPCC), global climate conditions have been changing over the past century and are set to become generally warmer throughout the 21st century [92]. When ill-designed buildings confront the warmer weather conditions, overheating of indoor environments and soaring energy demands may become likely due to increased solar heat inputs through the glazing, as well as convective and conductive heat gains through the building envelope. Hong Kong is located in the Köppen-Geriger climate classification of ''Cfa'' (Humid Subtropical Climate) and experiences a long hot and humid summer [1]. Local electricity generation is by far the biggest contributor (about 65%) to carbon emissions, and 92.7% of the electricity are consumed in the building sector [2,3]. Moreover, anthropogenic climate change has caused a continuous increase in temperature records in Hong Kong, resulting in an average rise of 0.17 °C every decade from 1989 to 2018 [4]. Consequently, electricity consumption per capita in the residential building sector is significantly increased from 3.0 GJ in 1989 to 5.9 GJ in 2018 [5]. More importantly, the lifespan of new residential buildings is expected to be about over 100 years due to the progress of building materials and technologies and the existing buildings still may last for several decades. Thus, both the existing and new buildings would need to be prepared for the worsening climate conditions, which would inevitably increase future energy demands and the frequency of overheated days. Since passive design strategies, such as exterior solar shading, fenestration system, and natural ventilation, have been often adopted in some nearly net zero energy buildings [6] and proved effective for minimizing building energy consumption in hot and humid climates [7,8], a thorough understanding of passive design strategies in the context of future climate change is critical for combating the exacerbated energy consumption and designing resilient buildings. Particularly, the future climate change would have the most significant impacts

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https://doi.org/10.1016/j.enbuild.2020.110469
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on the building energy use in cities with hot summer and warm winter climates where the buildings cooling requirements are inevitably high [9]. In other words, passive design strategies that can alleviate the impacts due to future weather conditions would have greater energy saving potentials. In addition, since the anthropogenic heat release from the increased air-conditioning usage would deteriorate the micro-climate and exacerbate the situation in some urban areas [10], the demands of using passive design strategies would be further increased in these areas. Therefore, it is imperative to rethink the effectiveness of passive design strategies under the changing climate context in order to inform architects the proper use of passive design strategies for maximizing the indoor thermal comfort and minimizing the energy demand.

1.2. Overview of previous studies

Passive design strategies include, but are not limited to, the building layout design, shading devices, envelop thermophysics, fenestration and infiltration & air-tightness [11]. Proper passive designs can be implemented by architects at the early design stage to achieve a high building performance. To counteract the impacts of climate change, various passive adaptation strategies were appraised by researchers worldwide.

In the Netherlands, van Hooff et al. [12,13] investigated six passive design measures for a Dutch terraced house. The external shading and additional natural ventilation strategies were found to be the most effective ways to improve building performance. Similarly, Porrit et al. [14] ranked the effectiveness of the single and combined mitigating interventions for UK dwellings and indicated that the combination of different interventions is necessary to eliminate the indoor overheating and reduce the building heating load. In Brazil, Triana et al. [15] evaluated the energy performance of isolated adaptation measures by cooling and heating degree-hours. In Australia, Ren et al. [16] investigated several adaptation measures for residential buildings and suggested that improving building envelope performance and installing on-site solar PVs are cost-effective strategies for adapting to the future climate. With the application of a simplified statistical model, Nik et al. [17] evaluated the energy saving potential of nine retrofitting measures for Swedish residential buildings and found that the combination of highly insulated building walls and windows is the most effective retrofitting measure. In Iran, Roshan et al. [18] developed Givoni's bioclimatic charts for examining the impacts of climate change on several bioclimatic design strategies. Another study in Taiwan by Hwang et al. [19,20] explored the energy saving effects for five passive design strategies and pointed out the combination of several passive strategies can neutralize the impacts of climate change. A recent study [21] carried out in Argentina analyzed the effects of future climates on several bioclimatic strategies and indicated that solar protection and natural ventilation are the most effective design strategies.

However, the simple method without any sensitivity analysis (SA) nor optimization is adopted in most of the above studies to investigate a combination of different interventions. More comprehensive methods can be found in the few recent studies. Several passive cooling solutions, e.g., building orientation, skylight surface area, envelope thermal insulation, and indoor setting temperature, for low-rise commercial buildings in France were optimized and mapped for current and future climate conditions in 2080 using the NSGA-II algorithm [22]. With the help of the Latin-hypercube sampling method, another study in the United States by Shen et al. [23] suggested that global climate change will alter the optimal solution of future energy conservation measures and hence the impacts of climate change should be taken into account when optimizing future retrofit projects.

1.3. Purpose of this study

In Hong Kong, most existing residential buildings are over 30 years old, and their poor building performance make them particularly vulnerable to climate change [24]. The implementation of proper passive design strategies is therefore all-the-more important in these buildings to neutralize the exacerbated energy demand and increase their ability to adapt to future climatic anomalies. Although the effectiveness of different passive design strategies in hot and humid climates has been verified by previous studies [7,8,25–28], most of these works have been conducted with a steady historical climate condition instead of a dynamic and changing future climate condition. Therefore, there is a serious lack of indication on the time-varying effectiveness of each design parameter by a prudent global SA method to understand and quantify the impacts of climate change on the effectiveness of these strategies. Furthermore, SA analyses without the quantification of the underlying range of uncertainties provide little value to policymakers. Uncertainties of the different climate change scenarios and climate models should be considered to provide a more flexible building design and a more comprehensive risk assessments for policymakers and architects at the early design stage. More importantly, the effect of adaptive thermal comfort, i.e., the acclimatization of occupants in mixed-mode residential buildings under the future climate conditions, has not been discussed in the above literature. These research gaps will be addressed in the current study. Set against the above background, this study aims to investigate the time-varying and dynamic effectiveness of different passive design strategies in face of climate change in the 21st century and propose practical guidelines for the resilient building designs.

2. Methods and datasets

This section presents the weather dataset, simulation tools, and methodologies used in this study. In specific, Section 2.1 describes briefly the preparation of the future climate hourly dataset for building simulation; Section 2.2 describes building characteristics, configuration of the building simulation model and thermal comfort criteria; Building Bio-Climatic Chart (BBCC) and selection of viable passive design strategies are detailed in Section 2.3; The simulation-based local and global SA methods for evaluating the time-varying effectiveness of different passive design parameters are given in Section 2.4. The methodological framework for this study is presented in Fig. 1. In addition, we study thermal comfort and energy saving rate as the indicator for the effectiveness in the BBCC and SA method, respectively.

2.1. Future weather dataset

In 2014, ''Representative Concentration Pathways (RCPs)'' were developed and published by the IPCC in the Fifth Assessment Report (AR5) to project future climate changes and to facilitate the assessments for adaptation and mitigation based on the possible socio-economic scenarios and driving forces [29,30]. These scenarios are the initial conditions and inputs for the General Circulation Models (GCMs) to forecast the climate change and obtain future climatic outputs. However, most of the GCMs have coarse spatial (100–300 km^2) and temporal (daily or monthly) resolutions [31] and would therefore require downscaling prior to the application in building performance simulation (BPS) tools, e.g., ESP-r, EnergyPlus, DOE-2, etc. Developed by Belcher et al. [32], the statistical downscaling method morphing is commonly used to construct future weather data for building energy research [33,34]. Two tools based on the morphing method, namely CCWorldWeatherGen and WeatherShift, are also available for researchers

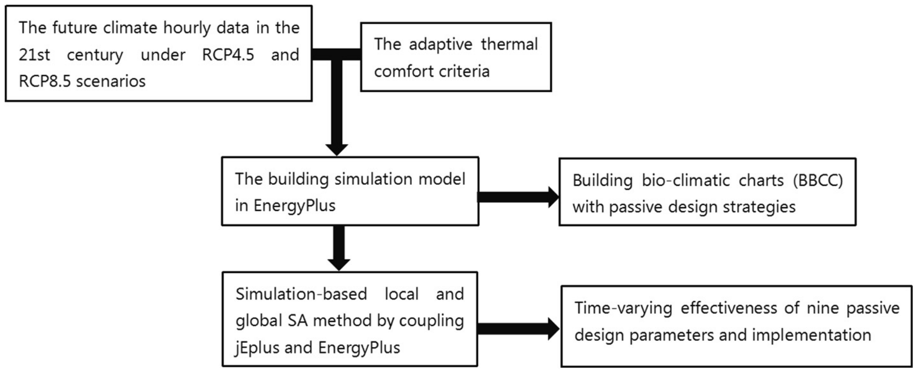

Fig. 1. Methodological framework of the study.

to create EnergyPlus weather files (EPW) [35]. However, it should be highlighted that the uncertainties and divergences between different GCMs and different scenarios should be considered [36,37].

Only the RCP4.5 and RCP8.5 scenarios belong to the core experiments of the CMIP5 database and are provided by all GCMs model groups [31]. So, in this study, the ensemble mean values from 24 GCMs under RCP4.5 and RCP8.5 scenarios are encapsulated into a local typical meteorological year (TMY) weather data, which is derived from the observed weather data by Hong Kong Observatory (HKO) from 1979 to 2003 [38]. The downscaled temperature anomaly from 24 GCMs and the ensemble mean temperature are presented in Fig. 2. All 24 GCMs are listed in Table A1 of Appendix. The weather data in the 21st century is divided into three time slices: the 2035 s, the 2065 s, and the 2090 s, to represent the near-term, the middle-term and long-term periods, respectively. The morphing algorithm and the process of development of these new future weather data are detailed in a previous study by the authors [39].

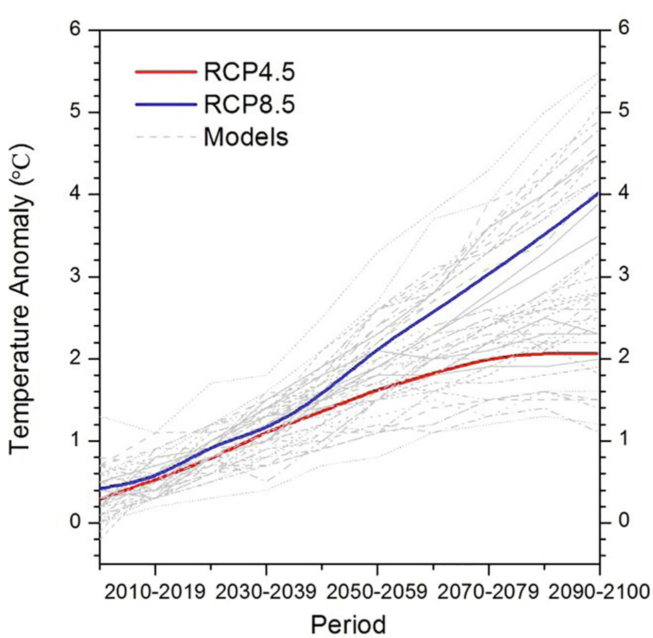

Fig. 2. Projected decadal temperature anomaly for Hong Kong under the RCP4.5 and RCP8.5 scenario. Gray curve represents results from a single GCM model; the red and blue solid lines represent the ensemble mean for RCP4.5 and RCP8.5 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.2. Building characteristics and thermal comfort criteria

Currently, almost half of the total population live in public rental housing (PRH) in Hong Kong [40]. To accommodate more citizens in the future, the local government plans to continue building these affordable PRH buildings. Most of the newly built PRH buildings, e.g., the Harmony and Concord types, have about 30–40 storeys and follow a cruciform floor plan (Fig. 3a). Designed for efficient construction, these buildings are built from prefabricated units and form around 70% of all PRH building types after the 2000 s (Fig. 3d) [41]. Since such PRH buildings are uniformly designed, constructed, and managed by the Hong Kong Housing Authority, the retrofitting of existing PRH buildings or upgrading of new ones are found to be easier [42]. Therefore, the Concord PRH type with a cruciform floor plan is selected as the indicative and typical case for further analyses.

2.2.1. Input of baseline simulation model

The widely used and extensively validated BPS tool, EnergyPlus, is applied for simulating the building performance under the different future climate scenarios. The newly developed future weather data mentioned in Section 2.1 are selected as the input weather data files. The detailed occupancy and operation schedules of Hong Kong residential buildings are set based on the standard residential schedule profiles in Hong Kong obtained from previous surveys [26,43,44], as shown in Table A2 in the Appendix. An occupant density of 0.077 people/m^2, calculated from an average living space per person of 13 m^2 [45], is adopted and the occupant load is 100 W/person. The light power density for living rooms and bedrooms is set to 14 and 17 W/m^2 respectively according to a local survey [46], and the equipment load is set to 142 W for each room [28]. The building envelope materials are constructed in the BPS tool according to the baseline model of the local green building standard BEAM Plus [47]. Some key information regarding the existing building physical parameters that are relevant to this study and the internal heat gains are presented in Table 1. To reduce the computational cost, only the habitable flats in the middle three floors were included in thermal calculations; the rest of the building were represented by adiabatic component blocks to provide the self-shading, as shown in Fig. 3b and Fig. 3c. More on the validated building model and assumptions can be found in the literature [28] and preceding studies by the authors [48,49]. To take into account the widely-used occupants-controlled natural ventilation in PRH, the changeover mixed-mode is selected in the model to control the window-opening schedule. The threshold of using air-conditioning and closing windows, i.e., the cooling setpoint temperature based on the adaptive thermal model assumption, will be discussed in Section 2.2.2. The Airflow Network model in EnergyPlus is used to achieve the

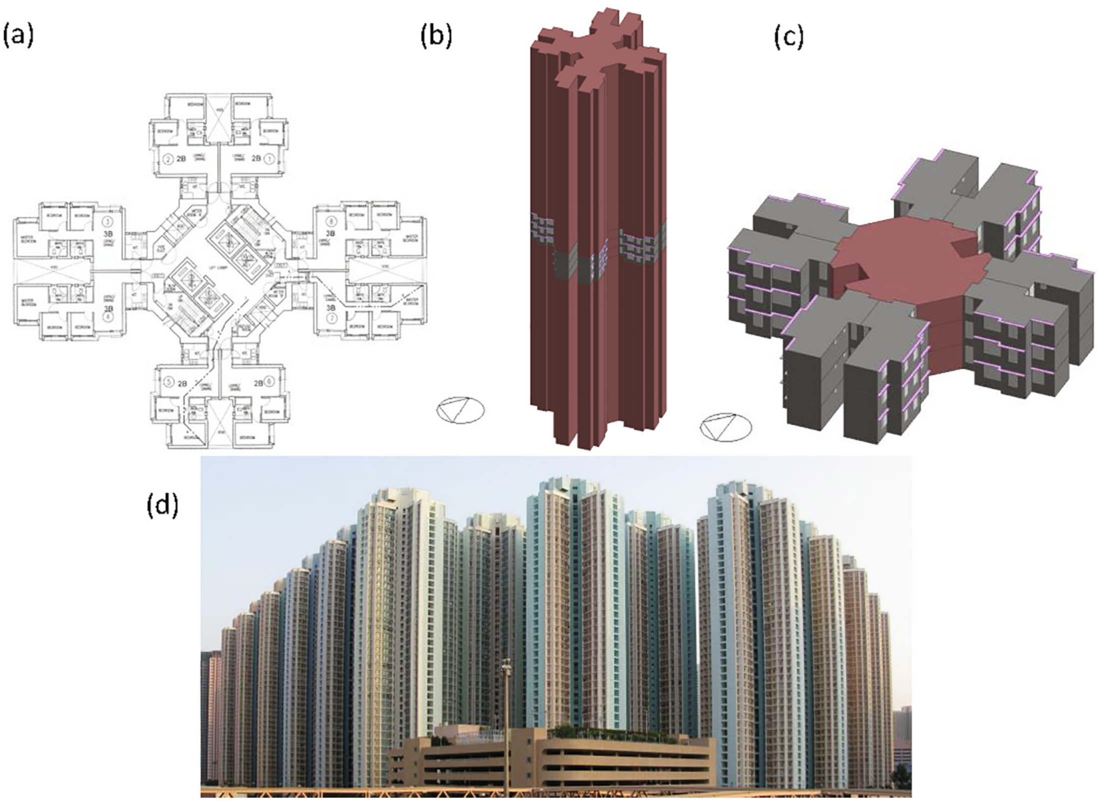

Fig. 3. Floor plan (a), the whole simulation model (b), mid-floor flats (c) and photo (d) of typical high-rise Public Rental Housing (PRH) buildings in Hong Kong.

Table 1
Building parameters for the models used in the simulations.

Parameters	Vaule
Total occupied floor area (m^2)	325.1
Cooled area (i.e. living room, bedroom) (m^2)	256.8
U-value of external wall ($W\ m^{-2}\ K^{-1}$)	2.75
Window to external wall ratio	0.148
Floor height (m)	2.75
Wall solar absorptance	0.58
Window Open Area Ratio	0.30
U-value of roof ($W\ m - 2\ K - 1$)	0.58
U-value of internal partition ($W\ m^{-2}\ K^{-1}$)	2.86
U-value of floor slab ($W\ m^{-2}\ K^{-1}$)	2.48
U-value of glazing ($W\ m^{-2}\ K^{-1}$)	5.75
Solar heat gain coefficient of glazing	0.6
Lighting power density (W/m^2)	14/17
Occupant load (W/person)	100
Misc. Equipment load (W)	142

detailed natural infiltration simulation for the mixed-mode buildings [50].

2.2.2. Thermal comfort criteria

In Hong Kong, the changeover mixed-mode is commonly used in the residential buildings where occupants control the opening of windows and the operation of air-conditioner. The occupants switch on air-conditioner and close windows only when the indoor thermal environment is intolerable for them. Hence, the thermal comfort criteria is essential for simulating whether indoor thermal comfort can be satisfied by natural ventilation or if air-conditioning is required. The steady-state comfort model, e.g., predicted mean vote (PMV), is not applicable to natural ventilation or mixed-mode buildings, because it has not considered the occupants' acclimatization effect due to the psychological thermal expectations [51,52]. For subtropical climates such as that of Hong Kong, the adaptive comfort standard (ACS) model was found to be more suitable for mixed-mode buildings by Luo et al [53]. The adaptive approach links the indoor comfort temperature with the outdoor air temperature. In other words, it assumes that the occupants in hot and humid climates are used to higher temperatures in summertime conditions. Hence, choosing a proper ACS model becomes fundamental to apply different strategies to achieve thermal comfort under a specific climate condition.

Reviewing different ACS models globally and regionally, the applicability of some commonly used international standards, i.e., EN16798 (formerly EN15251) [54] and ASHRAE 55 [55], has been deemed questionable by many scholars [56,57]. They indicated that adaptive comfort equations should change climate-by-climate, i.e. the adaptive equation for a specific climate should differ markedly from any worldwide standard. In hot and humid areas, some studies [58–60] have developed adaptive thermal comfort model from large-scale thermal comfort surveys. Other studies have developed ACS models in hot-humid climates based on the statistical *meta*-analysis of ASHRAE RP-884 database [61,62]. In this study, the ACS model developed by Cheng and Ng [63] is selected, which focuses on Hong Kong residential buildings and uses the ASHRAE RP-884 database. This model has a reasonably strong correlation coefficient of 0.72 between indoor neutral air temperature and average outdoor air temperature. It has also considered the adjustment of the local clothing insulation and extended the comfort criteria at elevated air speeds. This ACS model addresses the thermal adapting behaviors by introducing a function of monthly outdoor air temperature (T_o) in relation to the indoor neutral air temperature (T_i) as follows:

$$T_i = 16.7 + 0.33T_o \quad (1)$$

In terms of humidity influences, some recent studies [64,65] in cities with a similar hot and humid summer suggested that subjects started to show stronger thermal response when the humidity exceeded the limits from 17 g/kg to 18.8 g/kg. As for air movement influences, the elevated air velocity can affect the thermal sensation by enhancing convective and evaporative heat loss from the human body [66,67]. According to the ASHRAE Standard 55, the upper acceptable indoor temperature of this equation can be expanded by 1–2.5 °C provided there the wind speed is from 0.5 to 1.5 m/s. Considering the highly humid climate and prevalent use of fans in Hong Kong residential buildings, the thresholds for relative humidity from 20% to 80% and absolute humidity of 17 g/kg under still air suggested by Givoni [68] are still adopted in this study. When there is an elevated air velocity, the upper limits for relative and specific humidity are shifted to 90% and 19 g/kg, respectively. As for the comfort threshold temperature under the influence of elevated air speeds, the upper comfort limits provided by Cheng and Ng [63] are used in this study.

2.3. Building Bio-Climatic Chart (BBCC) and viable passive design strategies

The Building Bio-Climatic Chart (BBCC) provided by Milne-Givoni has been widely used in practice for architects and researchers [14,69]. Based on the different zones of bioclimatic diagrams, Milne and Givoni [70] recommend several bioclimatic and passive design strategies for different climates. Using the free-running simulated output data, i.e., indoor air temperature and relative humidity, from the baseline building model, the complete Hong Kong BBCC under the current TMY climate scenario was plotted as shown in Fig. 4. Based on the BBCC, the passive design strategies that are relevant for the subtropical climate, namely natural ventilation, dehumidification, internal heat gains, solar protection, can be easily selected in this study. The detailed temperature thresholds of different passive design strategies, i.e., the passive solar heating, internal heat gains and solar protection, are well documented in the literature [71]. The indirect passive design strategies, i.e., evaporative cooling, high thermal mass with nocturnal ventilation, and passive solar heating, are not considered in this study.

To validate the significance of passive design strategies in the context of changing climate, each design strategy, such as the ones considered in the BBCC, can be elaborated by the corresponding building physical parameters and can then be evaluated by the SA method. The relevant building design parameters for passive design should be selected and tested prior to the building design stage. It is also important to take into account the local climatic characteristics and building features when applying the various passive design strategies for existing or new buildings. The main features of public housing in Hong Kong were identified by Tan et al. [42] with the help of Hong Kong Housing Authority in 2018. They pointed out that energy saving design and devices are rarely adopted in the existing high-rise PRH buildings. Based on the identified characteristics of residential buildings and the policy considerations in Hong Kong, 28 applicable technologies and 18 retrofit policies were recommended in their report. Similarly, another study [72] proposed a series of green retrofit technologies for high-rise residential buildings in Hong Kong based on their feasibility and practicality for implementations. After reviewing the literature, the following viable passive adaption strategies relevant for the building envelope performance are selected within the scope of this study:

(1) Glazing material and window opening area. In Hong Kong, 96% of PRH buildings are equipped with aluminum windows with ordinary glazing [42] The solar heat gain through glazing has been proven to be the main culprit of the worsening indoor thermal environment in Hong Kong buildings [73]. The uniform replacement of existing windows by those with reflective coating or double glazing could be a cost-effective measure. Suitable passive solutions include the tinted low-e windows glazing, reflective glazing, and double or even triple glazing with air/argon gaps. There-

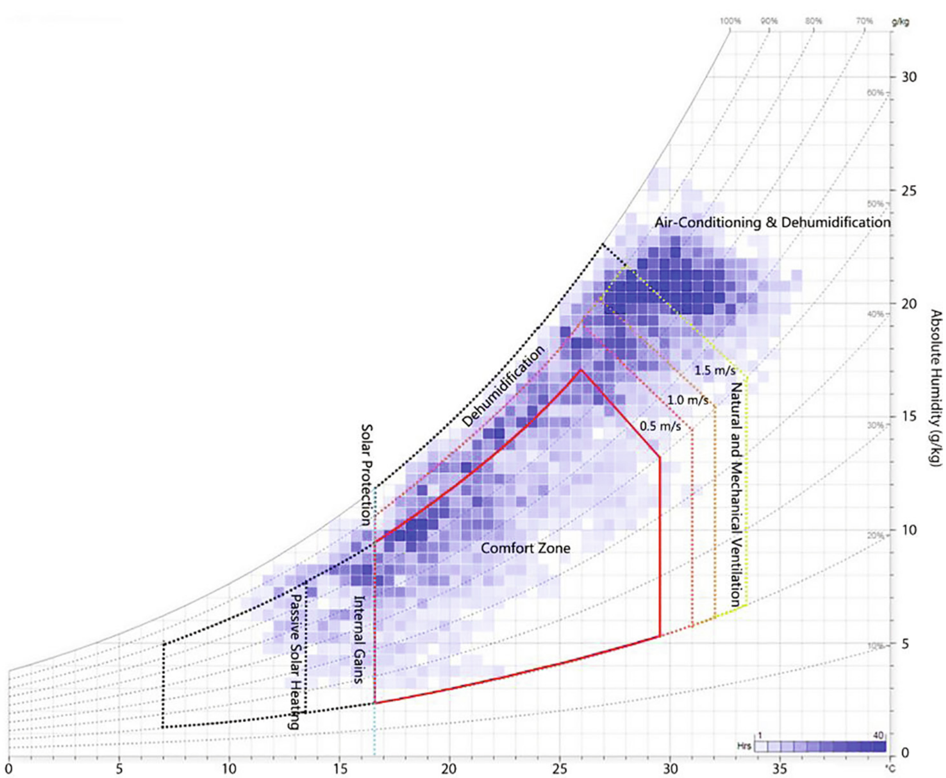

Fig. 4. The complete Hong Kong Building Bio-Climatic Chart (BBCC) under the TMY climate scenario.

fore, the commonly used parameters of Solar Heat Gain Coefficient (SHGC), as well as the Window U-value (WinU) of the glazing, are included in the sensitivity analysis. In terms of fenestration characteristics, the Window Open Area Ratio (WOAR) is selected to quantify the percentage of window opening. This parameter is often a good representation of the air change effectiveness when the window is opened to allow cooling by natural ventilation.

(2) Airtightness. A common source of air leakage is through the gaps and cracks between the frame of a component, such as a door or window, and the surface in which it is embedded. With respect to the deterioration of joints in the aged buildings, caulking techniques, e.g., sealing cracks for the frame of a component with an airtight seal, are feasible and common solutions in building retrofitting practices to reduce the air leakage between the external wall and windows [74]. Here, assuming that the existing airtightness can be upgraded from a poor to an excellent level by such techniques, the airtightness performance of external windows are represented by the infiltration air mass flowrate coefficient (IAFC), which are varied from 10^{-3} kg/s·m (to represent a poor performance) to 10^{-5} kg/s·m (to represent an excellent performance) in the simulations [50].

(3) Shading devices. Due to its ease of implementation, external shading is a popular strategy among researchers and architects [75]. External shading devices commonly include overhangs, side fins, and louvers. Their effects for improving energy efficiency of buildings in hot climate regions have been proven by previous studies [76]. Two shading devices, overhangs and side fins, are selected for further discussion. The upper limits of the length of overhangs and vertical fins are set based on the practice code of Hong Kong, which states that the sunshades within a projection of 750 mm are not regarded as obstructions to windows [77]. Taking a typical window height of 1.8 m and a widow width of 2.1 m in buildings, the maximum overhangs projection factor (OPF) is set to 0.42, while the upper bound of the side-fin projection factor (SPF) is set to 0.36.

(4) External wall insulation and thermal mass. The roof areas are substantially smaller than the wall areas due to the high-rise building characteristics in Hong Kong. Thus, the performance of external walls appear to be rather significant for the building energy efficiency. Enhancing the insulation of the building envelope is prevalent in the retrofitting practices. For example, Jia and Lee [78] found that U-values of walls have a tangible effect on the cooling load in Hong Kong residential buildings. Meantime, reflective or cool wall surfaces have been widely considered as effective solutions for decreasing the building cooling load [79,80]. Another important parameter of wall property is the heat capacity. Reilly and Kinnane [81] pointed out that high thermal mass structures for the reduction of energy consumption in hot climates are possible. Therefore, to further investigate the effectiveness of wall properties, the U-value of wall (WU), the wall solar absorptance (WSA) determining the solar heat gain from the wall surface, as well as the wall thermal admittance (Y-value, WY) relating to the wall thermal mass, are included and considered in the sensitivity analysis.

The range and distribution of all parameters of the above strategies are summarized in Table 2. The variation of the identified parameters are assumed to be of uniform distribution.

2.4. Sensitivity analysis methods

For a complex model, SA methods can help to identify the relative significance of input parameters on the output objectives [82]. At the early design stage, this method has been widely applied in the field of sustainable design to select the important design factors for building energy efficiency [83,84]. However, this useful method has rarely been adopted by architects in their practice due to the large experimental works and technical expertise required. SA methods can be grouped into three main methods, namely the screening method, local SA, and global SA [85]. The screening method is a method with an expensive computational cost for complex situations to identify and rank a massive number of design parameters. Therefore, only the latter two methods, i.e., local and global SA, are adopted for the above 9 parameters.

Local SA methods, also known as the differential method, are relatively straightforward and simple based on the one-parameter-at-a-time (OTA) method. After defining a baseline case (existing case), a qualitative analysis of the output response by each parameter, interpreted by its sensitivity coefficient, can be obtained by changing one parameter at a time. A sensitive coefficient (IC) is employed to quantify the importance of an input factor:

$$IC = \frac{\Delta OP/\left(\frac{OP_1+OP_2}{2}\right)}{\Delta IP/\left(\frac{IP_1+IP_2}{2}\right)} \tag{2}$$

Where ΔIP and ΔOP are the changes of input and output values, IP_1, IP_2 are two values of input, and OP_1, OP_2 are the corresponding output values.

As the local SA can be done quickly with a low computational cost, it is conducted as the initial test for the sensitivity of the building design parameters. However, there are limitations in interpreting the non-linear relationships between outputs and inputs and the interactions between different parameters in the local SA method. A more thorough examination of the linear or non-linear input–output relationships can be achieved by a global SA. The efficient and widely used Morris method is chosen to evaluate the output response by varying all the parameters in a wider domain at the same time. Moreover, the range and the probability distribution of input variables are incorporated, and the results can be easily interpreted graphically in the Morris method. The Elementary Effect (EE) is applied in the Morris method to evaluate coefficient of variation for each input variable i. This allows the determination of whether the effects of each parameter are a) Negligible (low average, low standard deviation), b) Linear and additive (high average, low standard deviation), or c) Non-linear or involved in interactions with other input parameters (high standard deviation). The EE for each input variable i is defined by

$$EE_i = \frac{y(x+e_i\Delta_i) - y(x)}{\Delta_i} \tag{3}$$

Where y is the output variable of interest and $\times$ is a vector of real input variables with k coordinates (i.e. number of parameters), e_i is a vector of zeros but with its i-th component equal to ± 1.

The sensitivity of output to each input variable i is evaluated by the average (μ_i) and the standard deviation (σ_i) of the EE:

$$\mu_i = \frac{1}{r}\sum_{i=1}^{r} EE_i \tag{4}$$

$$\sigma_i = \sqrt{\frac{1}{(r-1)}\sum_{i=1}^{r}(EE_i-\mu_i)^2} \tag{5}$$

Where r is the number of elementary effects related to each input variable i. μ is the mean value of the elementary effects to measure the importance of the design parameter, and σ is the standard deviation of the elementary effects to measure the non-linearity in input parameters of the model or interactions with other parameters involved in the model. To make sure that all parameters can be reasonably covered by a region of variation, the value of r is recommended to be varied from 4 to 10 in the literature [85]. In this study, the design parameter vector r is set to 8 to obtain a reliable result.

Table 2
Building design parameters for sensitivity analysis and their range and distribution.

No.	Parameter	Abbreviation	Unit	Distribution	Range
1	Window U-value	WinU	W/m^2-K	Uniform	0.85–5.75
2	Window Open Area Ratio	WOAR	%	Uniform	10–70
3	Window Solar Heat Gain Coefficient	SHGC	–	Uniform	0.2–0.6
4	Overhangs projection factor	OPF	–	Uniform	0–0.42
5	Side-fin projection factor	SPF	–	Uniform	0–0.36
6	U-value of walls	WU	W/m^2-K		0.40–3.85
7	Wall solar absorptance	WSA	–	Uniform	0.10–0.58
8	Y-value of walls	WY	W/m^2-K	Uniform	0.7–4.74
9	Infiltration air flow coefficient for cracks	IAFC	kg/s. m	Uniform	10^{-5} – 10^{-3}

The absolute average (μ_i^*) is also introduced here to classify input parameters by their order of importance, in spite of the sign of elementary effect. Moreover, the ratio between the standard deviation and absolute average (σ_i/μ_i^*) can be used as a measure of non-linearity effects for each parameter or interactions with other parameters [86]. By plotting both statistical indicators (σ_i and μ_i^*) and three straight lines with slopes σ_i/μ_i^* = 0.1, 0.5 and 1, respectively, influences on the objective can be presented graphically in the respective zones for almost linear (σ_i/μ_i^* <0.1), monotonic (0.1 < σ_i/μ_i^*< 0.5), almost monotonic (0.5 < σ_i/μ_i^*< 1) or non-monotonic non-linear influences (σ_i/μ_i^* > 1).

Taking the parameters of the existing building as the reference case, perturbations of input parameters with OTA are conducted by combining local SA and simulation tools. For the global SA, the huge number of building energy simulations with different parameter combinations are conducted with the software jEplus [87], which can automatically vary the corresponding input values in EnergyPlus. With regards to the 9 parameters, 8 elementary effects for each parameter, and 7 input weather scenarios, the minimum number of simulations using the Morris method is 560. After running all 560 simulations, the objective value of the job list, i.e., the building annual cooling load, is collected and analyzed by the Morris method. Finally, the results in SA will help us to select the important design factors for implementing into the residential buildings to demonstrate the energy saving effectiveness.

3. Results

3.1. Dynamic effectiveness of passive strategies in the BBCC

The complete Hong Kong Building Bio-Climatic Chart (BBCC), under RCP8.5 climate change scenario, are plotted and shown in Fig. 5, and the BBCC in RCP4.5 scenario are plotted in Appendix Figs. A1-A3. After counting the number of points falling in the different passive design zones, the number of hours requiring different passive design strategies can represent the significance of each passive design. Overall, it can be clearly seen that the locations of points are significantly shifted towards the right part of the psychrometric charts when comparing the TMY and RCP8.5–2090 s climate scenario. This trend means that the indoor thermal environment in Hong Kong residential buildings will unavoidably become more hot and humid in the future climate scenarios due to the climate change. Consequently, the number of discomfort hours requiring the use of air-conditioning and dehumidification almost doubles (from 2058 h in TMY to 4106 h in RCP8.5–2090 s), even when the ACS model is applied, which pushes the upper comfort temperature from 29.5 °C in the TMY to 30.5 °C in RCP8.5–2090 s, providing a slight relief for the increased energy consumption. Compared with the change in discomfort hours, the points falling in the comfort zone have a smaller change, decreasing from 3502 h in TMY to 3225 h in RCP8.5–2090 s. This may be attributable to the reduction of hours requiring internal heat gains and passive heating strategies during winter time as the climate becomes warmer, e.g., 392 h in TMY requiring internal heat gains are decreased to 125 h in RCP-2090 s. On the other hand, the warming climate causes the increased need for solar protection, e.g., the number of hours requiring solar protection increases from 8011 h in the TMY to 8505 h in RCP8.5–2090 s.

In terms of the change in amount of time requiring different passive strategies as observed in Fig. 6, the most characteristic change over the analyzed decades in the 21st century is the gradual decrease in effectiveness for most passive cooling design strategies over time, especially for ventilation. The utilization of natural and mechanical ventilation, the sum of ventilation hours at different air velocities, significantly decreases from 2019 h in TMY to 1238 h in RCP4.5–2090 s and 992 h in RCP8.5–2090 s. Additionally, the amount of time requiring the use of the different air velocities for cooling people is varied over the 21st century. The ventilation with 0.5 m/s is consistently the most demanded strategy (1087 and 506 h in TMY and RCP8.5–2090 s, respectively) for achieving thermal comfort, while the ventilation with a range of 0.5–1.0 m/s is of less importance (364 and 206 h in TMY and RCP8.5–2090 s respectively) for occupants. The results indicate that only using natural ventilation will cease to be sufficient to cooling the residential buildings in subtropical Hong Kong due to the increasing outdoor temperature in the future. Although the other passive strategies, e.g., passive solar heating and dehumidification, have a negligible significance for passive cooling, a similar decreasing trend of their effectiveness can be observed.

3.2. Dynamic effectiveness of passive strategies in the global SA

With the assistance of the global SA, the time-varying dynamic sensitivity coefficient of each passive design parameter for the building cooling load is identified and plotted in radar chart Fig. 7, and their relative percentage change is also plotted in Fig. 8 taking the sensitivity coefficient of TMY as the reference value. Table 3 shows the sensitivity indices of the 9 passive design parameters for building energy performance obtained from the global SA. The results of the initial test by the local SA are attached in the Appendix Table A3. For a quick understanding of the significance of each passive strategy, the cells are colored from dark red (highly sensitive) to dark green (negligibly sensitive).

The most remarkable observation from Fig. 7 and Fig. 8 is the deceasing significance of almost all design parameters over the 21st century, except for IFAC. This means that almost all passive design parameters will become relatively less significant for mitigating the energy consumption in the future compared with the TMY climate scenario. This is attributable to the considerably increased building energy use, i.e., the denominator, in the future climatic scenarios. In contrast, the significance of IFAC is expected to increase by 157% and 329% for RCP4.5 and RCP8.5 in 2090 s, as shown in Fig. 8. This reveals that the importance of better airtightness for buildings which require a significantly increased amount of air-conditioning in the future.

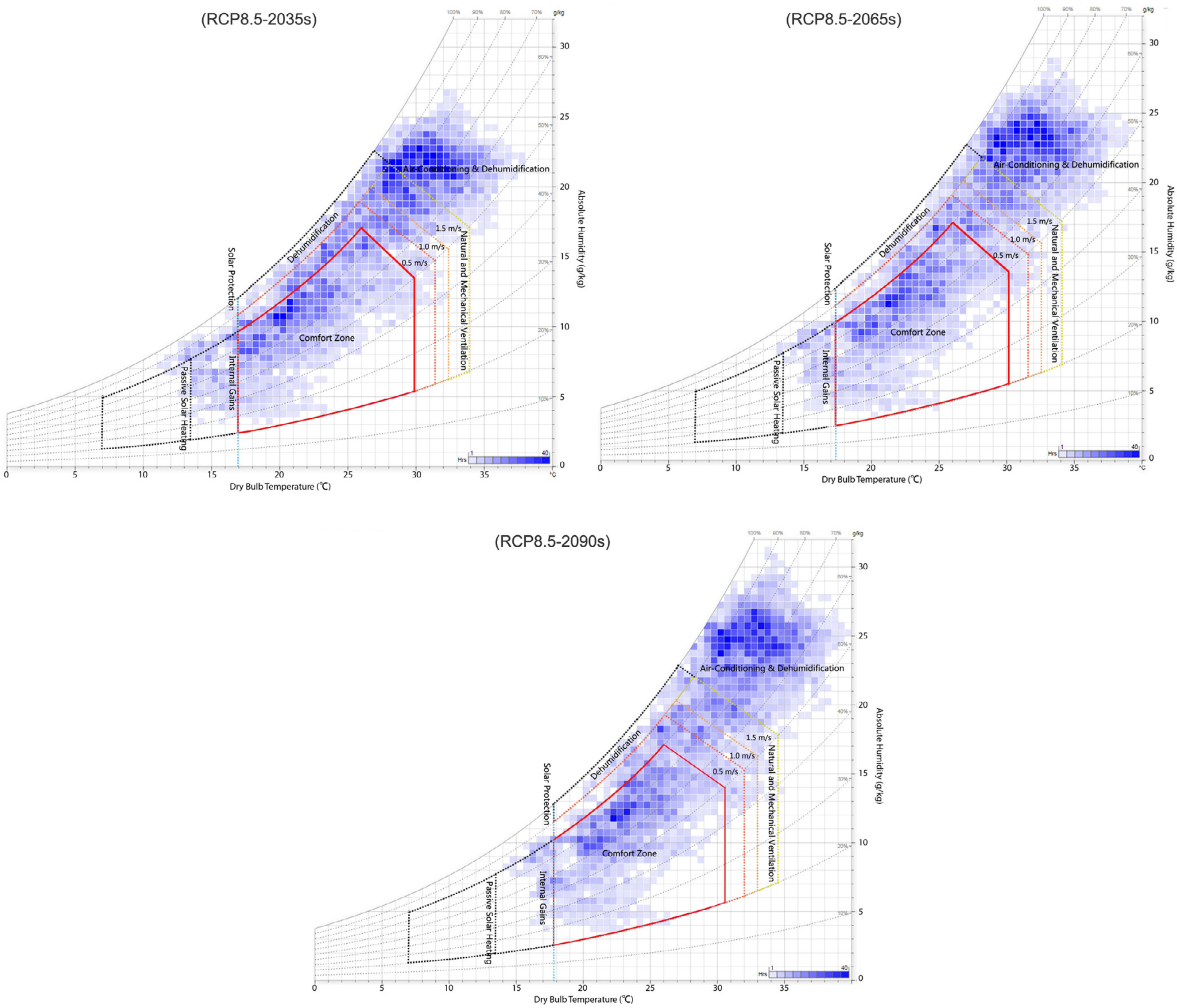

Fig. 5. The complete Hong Kong Building Bio-Climatic Chart (BBCC) under the different climate scenarios.

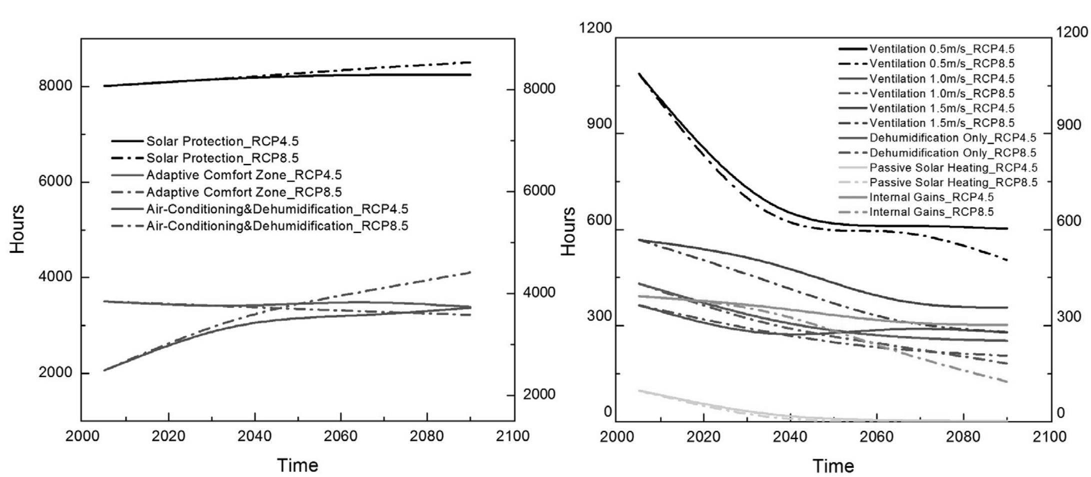

Fig. 6. The number of hours requiring different passive design strategies over time.

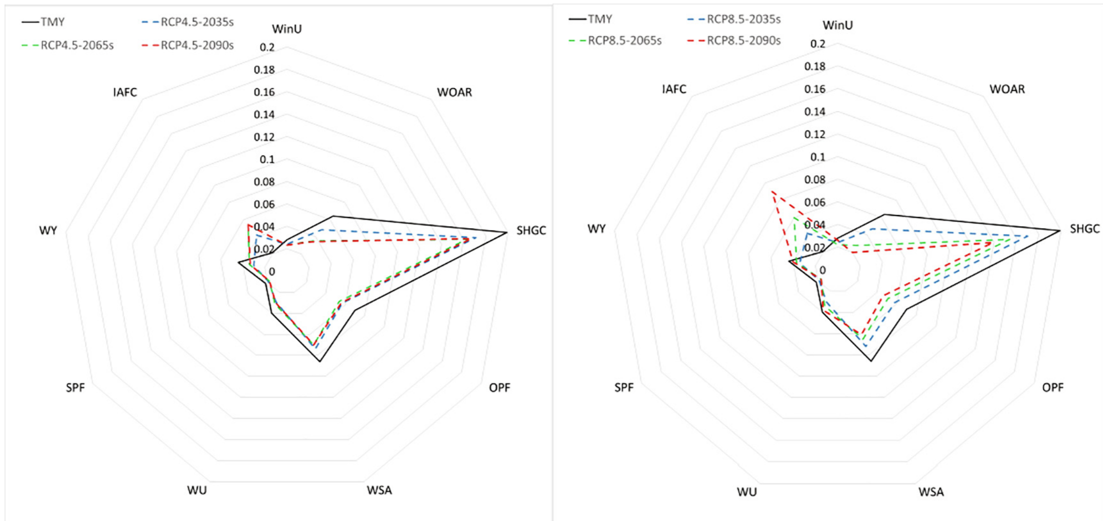

Fig. 7. The value of average (μ^*) in the global SA of passive design parameters for the cooling load in radar chars.

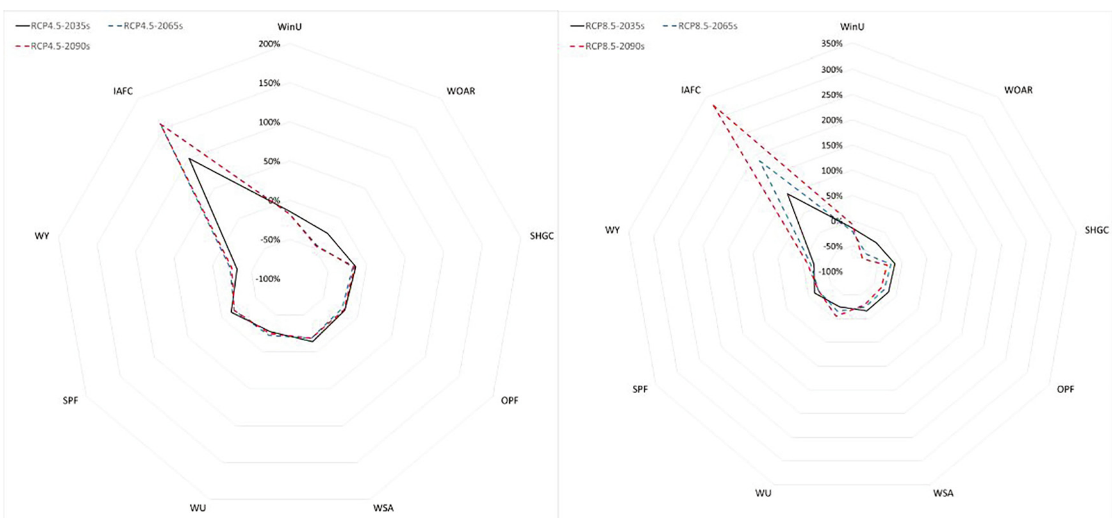

Fig. 8. The relative change of average (μ^*) in the global SA of passive design parameters for the cooling load in radar chars.

Table 3
Sensitivity indices of passive design parameters in the global SA for building energy saving under different climate scenarios.

Input parameter	TMY		RCP4.5–2035 s		RCP4.5–2065 s		RCP4.5–2090 s		RCP8.5–2035 s		RCP8.5–2065 s		RCP8.5–2090 s	
	μ^*	σ	μ^*	σ	μ^*	σ	μ^*	σ	μ^*	σ	μ^*	σ	μ^*	σ
WinU	0.028	0.027	0.024	0.020	0.023	0.018	0.023	0.019	0.024	0.019	0.022	0.018	0.026	0.017
WOAR	0.064	0.036	0.048	0.008	0.035	0.007	0.034	0.004	0.047	0.006	0.028	0.009	0.020	0.023
SHGC	0.199	0.045	0.171	0.030	0.163	0.027	0.167	0.028	0.170	0.030	0.154	0.026	0.139	0.026
OPF	0.070	0.016	0.057	0.011	0.054	0.010	0.056	0.011	0.058	0.011	0.051	0.010	0.046	0.009
SPF	0.022	0.010	0.019	0.009	0.018	0.010	0.018	0.009	0.019	0.010	0.017	0.009	0.017	0.010
WU	0.040	0.030	0.029	0.020	0.031	0.015	0.030	0.016	0.031	0.020	0.034	0.030	0.038	0.034
WSA	0.086	0.046	0.074	0.033	0.070	0.030	0.070	0.031	0.072	0.032	0.065	0.028	0.061	0.023
WY	0.044	0.028	0.030	0.024	0.034	0.031	0.033	0.025	0.034	0.026	0.037	0.030	0.041	0.024
IAFC	0.021	0.007	0.042	0.005	0.054	0.006	0.054	0.006	0.042	0.006	0.060	0.008	0.090	0.015

Note: Dark red color means highly sensitive and dark green means negligibly sensitive.

Amongst the building design parameters evaluated, the SHGC emerges as the most significant design consideration with sensitivity coefficient of 0.167 and 0.139 for RCP4.5 and RCP8.5 in 2090 s, while the WSA and OPF appear as the second and third most important factors in the global SA apart from IFAC. Moreover, the significance of solar protection strategies has a more dramatic decreasing trend compared to the parameters related to insulation, i.e., WinU and WU. For example, the μ^* of SHGC decreases from 0.199 to 0.139 (30%), the μ^* of OPF decreases from 0.071 to 0.046 (35%), and the μ^* of WSA decreases from 0.086 to 0.061 (29%), for TMY and RCP8.5–2090 s respectively. Whereas for WinU and WU, their μ^* only decreased slightly by 7% and 5%, respectively, between the TMY and RCP8.5–2090 s. Another noticeable characteristic of the relative change trends of each design parameter in Fig. 8 is that the effectiveness of an increased WOAR has the most dramatic decreasing trend amongst all parameters, with its μ^* dropping by 47% from 0.064 in TMY to 0.034 in RCP4.5–2090 s and 69% from 0.064 in TMY to 0.020 in RCP8.5–2090 s.

The absolute average (μ^*) and standard deviation (σ) for each adaptation strategy obtained from the global SA are presented in Fig. 9. The σ/μ^* of most design parameters are fall within the range of 0.1 to 1.0, meaning that most parameters have both linear and non-linear/correlated impacts on the building energy efficiency objective. In all climate scenarios, the σ/μ^* for OPF, IAFC and SHGC are the closest to 0.1, meaning that these three parameters have an almost linear influence on the building energy performance. On the other hand, the σ/μ^* for WinU, WU, and WY lie almost on the non-monotonic and non-linear line (σ/μ^*=1.0), suggesting that the combinations of such strategies may not bring about further linear energy savings, e.g., a building with super insulated windows but light weight walls would probably not perform well. The other parameters, e.g., WSA, WOAR, and SPF, have an almost monotonic effect on the building energy performance.

3.3. Practical implementation of the sensitive strategies into the residential buildings

To demonstrate the energy saving effectiveness of using different passive design strategies under the current and future climate change scenarios, the most sensitive building design parameters found from the SA results in Table 3, including WSA, SHGC, WOAR and OPF, are chosen to retrofit a residential building with holistic passive adaptation strategies in the current TMY scenario. In contrast, the effectiveness of window frames' airtightness and external wall insulation has a relatively significant increase in the future weather conditions, while the effectiveness of a bigger window openable area has a considerable decrease. Therefore, passive retrofit measures with the other two parameters IAFC and WU are adopted but WOAR are discarded for retrofitting buildings in the future RCP8.5–2090 s scenario. Description of the different feasible retrofit measures under the current and future climate conditions are presented in Table 4. Assuming that the value of the above parameters which is expected to achieve the most energy saving are adopted for retrofitting the existing PRH building, the indoor air temperature and the energy demands before and after retrofitting are plotted in the psychometric charts shown in Fig. 10 and compared in Table 5.

After calculating the hours requiring ventilation before and after retrofitting, the hours requiring ventilation in RCP8.5–2090 s have a significant increase of 19.4%, 11.2%, and 68.6% for air speeds of 0.5 m/s, 1.0 m/s, and 1.5 m/s, respectively. In contrast to the baseline building before retrofitting, the elevated air speed is more required for achieving thermal comfort when the holistic passive designs are implemented. Meanwhile, the annual and peak cooling load show a significant reduction of 55.1% and 38.1% for TMY and 56.7% and 64.5% for RCP8.5–2090 s. It means that the implementation of these passive strategies can neutralize the increase of building energy demand from TMY to RCP8.5–2090 s. Considerable reductions in the maximum indoor temperature of 3.6 °C (from 35.8 °C to 32.2 °C) for TMY and 3.1 °C (from 39.2 °C to 36.1 °C) for RCP8.5–2090 s can be also observed after implementing the above sensitive passive design strategies. The results show promising potentials for the adoption of holistic energy-efficient passive designs when retrofitting residential buildings in Hong Kong to prepare them for future climate conditions.

4. Discussion

4.1. Key findings and recommendations

Based on the findings from this study, the solar protection is still the most sensitive strategy for building energy efficiency but it has a more dramatic decreasing trend over time compared to the parameters related to insulation. Although the parameters on envelope insulation have a relatively minor effect on the overall building performance comparing with the solar protection strate-

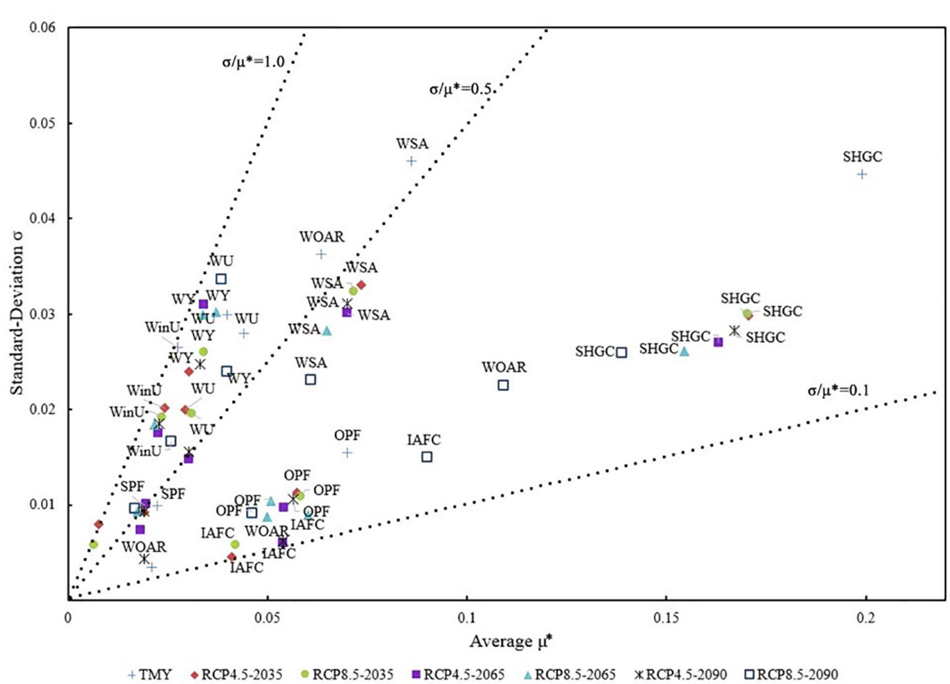

Fig. 9. Absolute average (μ^*) and standard deviation (σ) for each adaptation strategy using Morris analysis on the building energy saving. The highly sensitive strategies are remarked with names and the lines on the plot represent the slope (σ/μ^*) at the values of 0.1, 0.5, and 1.

Table 4
Description of the adopted passive retrofit measures under the current and future climate conditions.

Passive Strategies	S1: Window Shading	S2: Glazing Replacement	S3: Window Openable Area	S4: External Window Frame Airtightness	S5: Wall Solar Absorptance	S6: External Wall Insulation
Retrofit	Measures in TMY	Adding 0.7 m overhang shading panels to windows(OPF = 0.42)	Replacing single clear panel to Low-e coated grey panel (SHGC = 0.27)	Increasing openable windows area (WOAR = 70%)	None	Replacing external wall tiles to white color (WSA = 0.3)
None						
Retrofit	Measures in RCP8.5–2095 s	Adding 0.7 m overhang shading panels to windows(OPF = 0.42)	Replacing single clear panel to Low-e coated grey panel (SHGC = 0.27)	None	Sealing cracks for external window frames (IAFC = 1 $\times$ 10^{-5} kg/s. m)	Replacing external wall tile to white color (WSA = 0.3)
Adding a 10 mm inner layer of	expanded polystyrene (EPS) (WU = 1.80 W/m^2-K, WY = 2.1 W/m^2-K)					

Note: None means the significance of retrofit measures is comparatively small and not suggested in that specific weather condition.

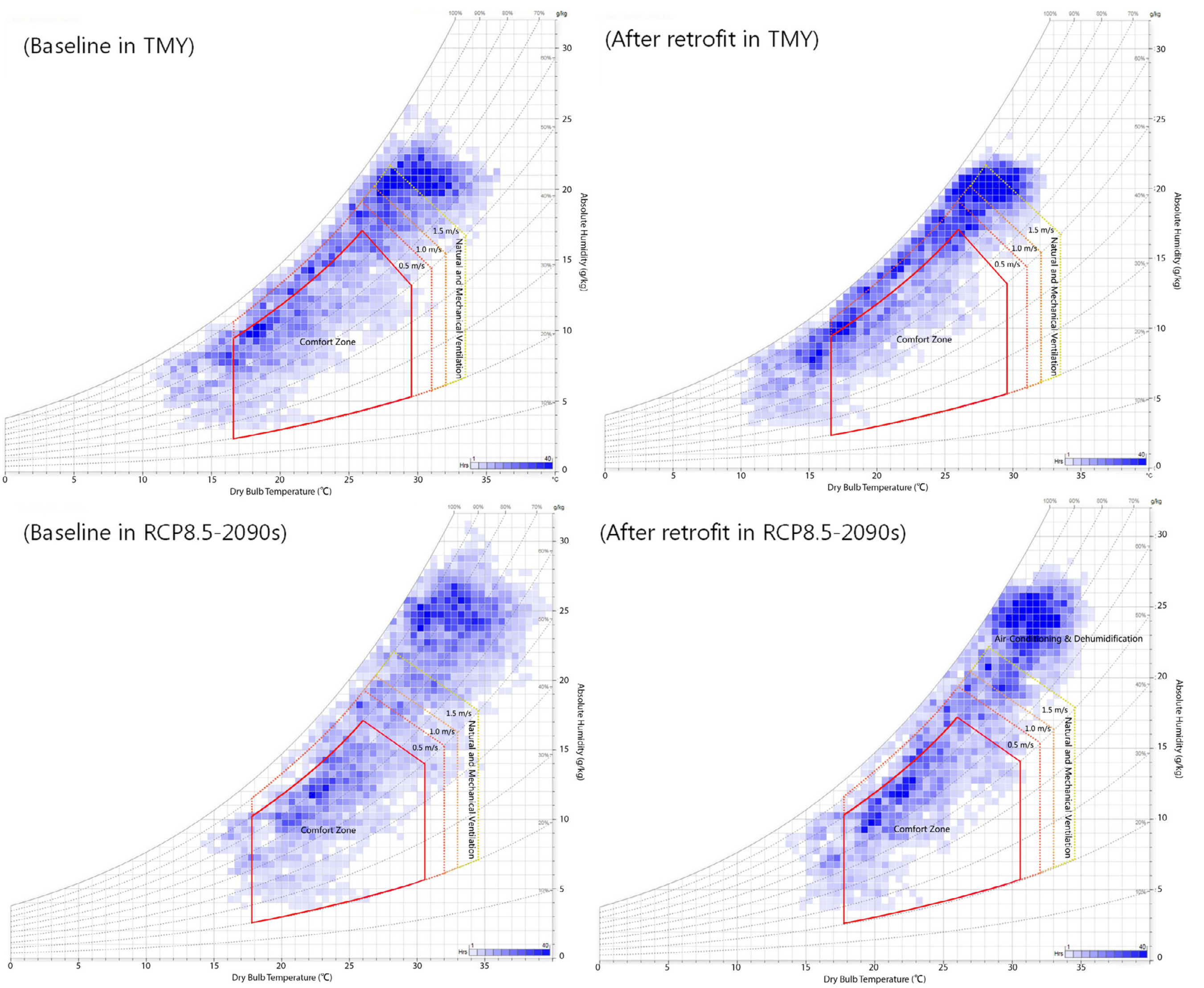

Fig. 10. Comparison of psychometric charts before (a) and after (b) implementation of the most sensitive strategies under the TMY and RCP8.5–2090 s climate scenarios.

gies, their importance will become more evident under the future climate conditions with increased temperatures. This can be attributable to the consistent increase of air temperature and the inconsistent increase of solar radiation in Hong Kong for the future

Table 5
Results of building performance before and after implementing of sensitive strategies into the residential building.

Building model	Hours requiring ventilation of 0.5 m/s	Hours requiring ventilation of 1.0 m/s	Hours requiring ventilation of 1.5 m/s	Maximum temperature (°C)	Hours in adaptive comfort zone	Annual cooling load (kWh/m^2)	Peak cooling load (kW)
The baseline in TMY	1087	364	568	35.8	3502	86.18	6.62
Retrofitting with the holistic passive strategies	1320	413	987	32.2	2875	38.71	4.11
The baseline in RCP8.5–2090 s	506	206	280	39.2	3225	201.22	9.59
Retrofitting with the holistic passive strategies	604	229	472	36.1	3409	87.15	3.40

Note: The maximum temperature and comfort hours are calculated based on the free-running model, while the calculation of annual and peak load is based on the air-conditioning model.

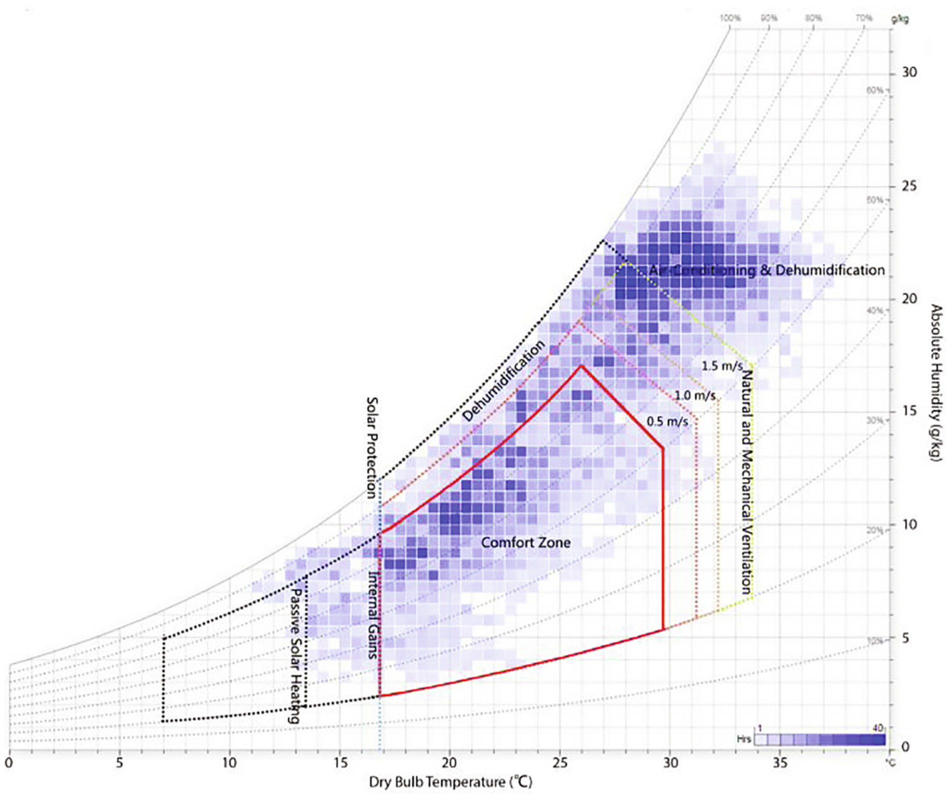

Fig. A1. The complete Hong Kong Building Bio-Climatic Chart (BBCC) under the RCP4.5–2035 s climate scenario.

climate scenarios. More detailed information about increase of air temperature and solar radiation in Hong Kong can be found in the literature [39,88]. It is also worth noting that the external shading and filming for the glazing have a straightforward influence on the building energy performance based on the linear or non-linear analysis in Fig. 9. Moreover, the range of OPF and SPF was limited to the maximum length (750 mm) of shading panels according to the local code and incorporated in global SA as mentioned in Section 2.3. It means that the effectiveness of external shading still have great potentials to be improved if the maximum length of external shading panels could be further increased.

More importantly, the linear or non-linear relationships between the building energy performance and each passive design parameter in Fig. 9 should be highlighted such that architects can better determine how to apply the passive strategies at the early design stage. For instance, parameters related to insulation lie almost on the non-monotonic and non-linear line, which suggest that improving the insulation of walls and windows is costly but may not produce building with much better performance, and therefore may not be cost-effective. This finding is in agreement with findings in hot and humid climates reported in the literature [20,26], but differs with those for other areas with cold climates [14,17,18] as the highly insulated envelope is more suitable for the cold climates. By contrast, openable windows areas and better airtightness of window frames have an almost linear and monotonic effect on building performance. Moreover, the effectiveness of airtightness is expected to increase up to 329% by the end of this century, while the effectiveness of increasing WOAR will substantially decrease over time. From these findings, we therefore encourage architects to pay more attention to the external shading and natural ventilation design under the current weather conditions and recommend policy makers to provide more flexible limits

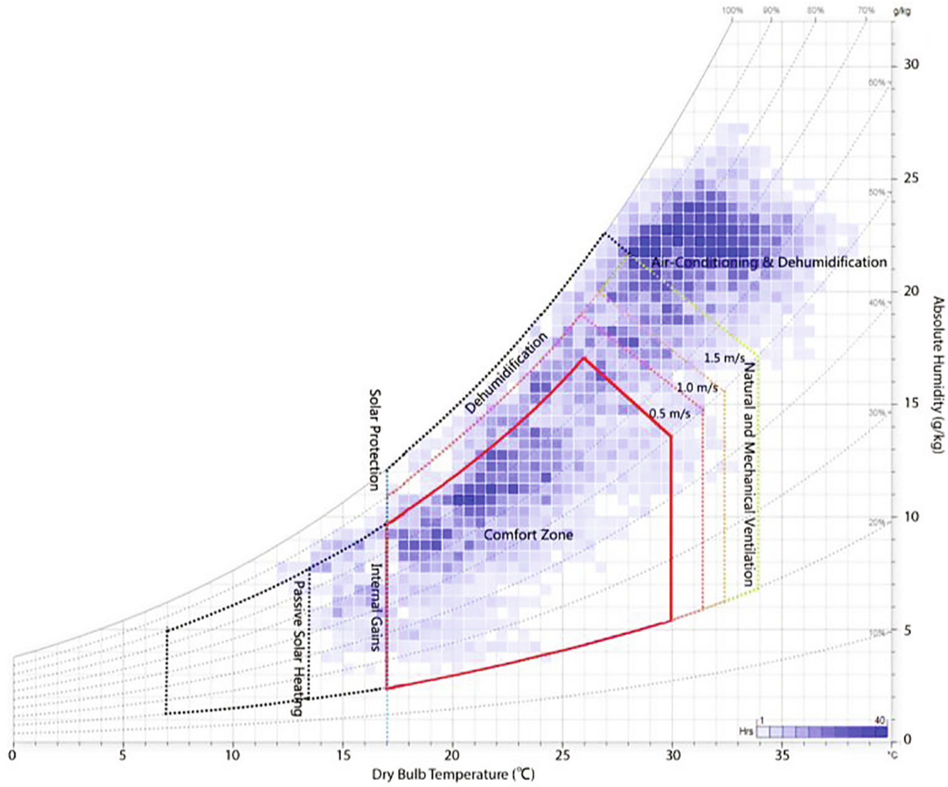

Fig. A2. The complete Hong Kong Building Bio-Climatic Chart (BBCC) under the RCP4.5–2065 s climate scenario.

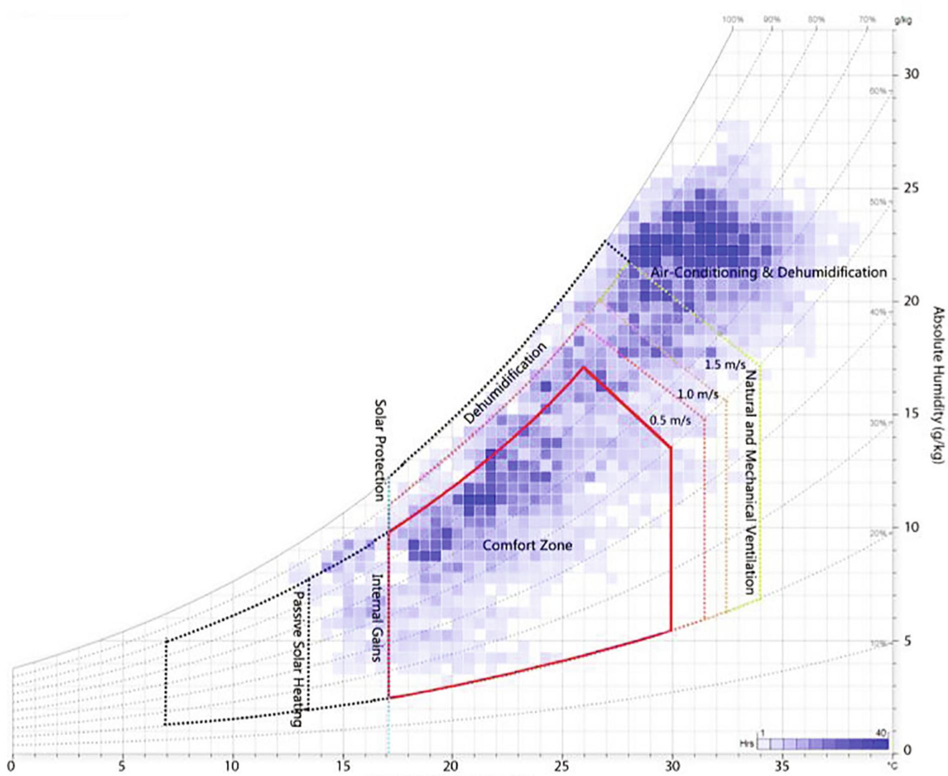

Fig. A3. The complete Hong Kong Building Bio-Climatic Chart (BBCC) under the RCP4.5_2090s climate scenario.

Table A1
List of CMIP5 general circulation models applied in this study.

Model Designation	Modelling Group	Group Acroynm	Scenarios
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization	CSIRO	RCP4.5, RCP8.5
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	BCC	RCP4.5, RCP8.5, RCP2.6, RCP6.0
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University	GCESS, BNU	RCP4.5, RCP8.5, RCP2.6
CanESM2	Canadian Centre for Climate Modelling and Analysis	CCCma	RCP4.5, RCP8.5, RCP2.6
CNRM-CM5	Centre National de Recherches Météorologiques	CNRM	RCP4.5, RCP8.5, RCP2.6
CSIRO-Mk3-6–0	Commonwealth Scientific and Industrial Research Organization	CSIRO	RCP4.5, RCP8.5, RCP2.6, RCP6.0
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	RCP4.5, RCP8.5, RCP6.0
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	RCP4.5, RCP8.5, RCP6.0
HadGEM2-CC	Met Office Hadley Centre	MOHC	RCP4.5, RCP8.5
INM-CM4	Institute for Numerical Mathematics	INM	RCP4.5, RCP8.5
IPSL-CM5A-LR	Institut Pierre-Simon Laplace	IPSL	RCP4.5, RCP8.5, RCP2.6, RCP6.0
IPSL-CM5A-MR	Institut Pierre-Simon Laplace	IPSL	RCP4.5, RCP8.5, RCP2.6, RCP6.0
IPSL-CM5B-LR	Institut Pierre-Simon Laplace	IPSL	RCP4.5, RCP8.5
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, The University of Tokyo	MIROC	RCP4.5, RCP8.5, RCP2.6, RCP6.0
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, The University of Tokyo	MIROC	RCP4.5, RCP8.5
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute, The University of Tokyo	MIROC	RCP4.5, RCP8.5, RCP2.6, RCP6.0
MPI-ESM-LR	Max-Planck-Institut für Meteorologie	MPI	RCP4.5, RCP8.5, RCP2.6
MRI-CGCM	Meteorological Research Institute	MRI	RCP4.5, RCP8.5, RCP6.0
Nor-ESM1-M	Norwegian Climate Centre	NCC	RCP4.5, RCP8.5, RCP2.6, RCP6.0
MPI-ESM-MR	Max-Planck-Institut für Meteorologie	MPI	RCP4.5, RCP8.5, RCP2.6
ACCESS1-3	Commonwealth Scientific and Industrial Research Organization	CSIRO	RCP4.5, RCP8.5
BCC-CSM1-1-m	Beijing Climate Center, China Meteorological Administration	BCC	RCP4.5, RCP8.5, RCP2.6, RCP6.0
CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	RCP4.5, RCP8.5
CMCC-CM	Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	RCP4.5, RCP8.5

for the maximum length of external shading projection and stringent regulations for limiting the airtightness performance of external window frames in the future.

In the local practice, the Hong Kong BEAM Plus assessment offers credits and incentives to building passive designs, including natural ventilation and building envelope design. The local practice code APP-156 also requires that the residential thermal transfer value (RTTV) should not exceed 14 W/m^2 for all new buildings or major revision of buildings since 2015 [77]. It takes into consideration the heat conduction and the solar radiation through the opaque walls and glass windows. In light of the results from the current study, the change of importance for envelope design parameters under the changing climate can further enable policymakers to revise it and formulate more timely regulations. The coefficients in the RTTV formula should be amended according to the different climate scenarios, e.g., the coefficient of solar radiation for glazing should be decreased while the coefficient of thermal conduction for opaque wall should be increased based on the time-varying effectiveness of different parameters. Moreover, the importance of the windows' IAFC, WOAR and the walls' Y-value in the future should be taken into account in the RTTV formula.

4.2. Comparison between BBCC and SA method

Comparing the results between BBCC and SA method, a similar trend can be confirmed in both methods about the decreasing effectiveness by ventilation in the future weather conditions. This observed decreasing efficiency of ventilation in the future may be due to either the so-called 'switching behaviour' of occupants when the indoor thermal environment is intolerable, or the decreasing cooling potentials of the outdoor temperature. Simply put, under the future climate conditions, the outdoor temperature is often substantially higher than the threshold for indoor thermal comfort. Therefore, the duration of using air-conditioning and closing windows is significantly increased in residential buildings employing the hybrid ventilation mode. A similar conclusion was found in southern European locations in the literature [89]. This is also consistent with findings in a previous study on the efficiency of night ventilation in residential buildings [90] and another study in the USA [91]. It is also worth noting that, although we have considered the operable window area ratio in the SA method to quantify the significance of air change rate between the outdoor and indoor, the BBCC can provide more information about the different elevated air speed to expand the thermal comfort zone, which is critical for the detailed ventilation design for indoor thermal environment.

Meanwhile, the two methods both reveal that solar protection is the most significant strategy for avoiding overheating in residential buildings in Hong Kong. However, the changing trend of the effectiveness of solar protections differs between the two methods. There appears to be some misleading information about the dynamic effectiveness of solar radiation using the BBCC method, because BBCC only takes air temperature as the threshold to quantify the importance of solar protection. Thus, the change of solar radiation dimension of outdoor weather conditions cannot be fully reflected in the psychometric charts.

Table A2
Building occupancy and operation schedule (habitable area) [28,43].

Hour	Occupancy(Weekdays)	Occupancy(Weekends)	Equipment (Mon-Sun)	Lighting (Mon-Sun)
1	1	1	0.2	0
2	1	1	0.2	0
3	1	1	0.2	0
4	1	1	0.2	0
5	1	1	0.2	0
6	1	1	0.2	0
7	1	1	0.37	0.3
8	0.7	0.9	0.54	0.5
9	0.4	0.7	0.54	0.3
10	0.3	0.6	0.54	0
11	0.3	0.5	0.54	0
12	0.2	0.4	0.54	0
13	0.2	0.3	0.54	0
14	0.2	0.3	0.63	0.5
15	0.2	0.3	0.43	0
16	0.3	0.3	0.43	0
17	0.3	0.4	0.43	0
18	0.4	0.4	0.43	0
19	0.6	0.5	0.43	0.5
20	0.7	0.6	1	1
21	0.8	0.7	1	1
22	0.9	0.8	1	1
23	0.9	0.9	1	1
24	1	1	1	0.5

Table A3
Sensitivity coefficients of passive design parameters in local SA for building cooling load under different climate scenarios.

Input parameter	TMY		RCP4.5–2035 s		RCP4.5–2065 s		RCP4.5–2090 s		RCP8.5–2035 s		RCP8.5–2065 s		RCP8.5–2090 s	
	IC	R^2	IC	R^2	IC	R^2	IC	R^2	IC	R^2	IC	R^2	IC	R^2
WinU	0.207	0.988	0.155	0.99	0.131	0.991	0.135	0.991	0.153	0.990	0.114	0.990	0.081	0.992
WOAR	0.155	0.892	0.074	0.442	0.056	0.950	0.050	0.963	0.074	0.071	0.040	0.997	0.019	0.995
SHGC	0.547	0.999	0.396	0.999	0.348	0.999	0.344	0.999	0.392	0.999	0.305	0.999	0.238	0.996
OPF	0.123	0.655	0.082	0.978	0.077	0.993	0.075	0.995	0.087	0.990	0.066	0.989	0.049	0.995
SPF	0.051	0.642	0.036	0.988	0.032	0.981	0.029	0.984	0.036	0.965	0.026	0.985	0.019	0.988
WU	0.017	0.891	0.035	0.997	0.046	0.999	0.044	0.999	0.031	0.997	0.064	0.999	0.100	0.999
WSA	0.329	0.999	0.239	0.999	0.224	0.999	0.228	0.999	0.247	0.999	0.221	0.999	0.207	0.989
WY	0.021	0.582	0.032	0.837	0.051	0.913	0.047	0.904	0.033	0.857	0.068	0.915	0.107	0.943
IAFC	0.052	0.986	0.061	0.993	0.068	0.984	0.070	0.995	0.061	0.993	0.074	0.998	0.088	0.995

Note: Dark red color means highly sensitive and dark green means negligibly sensitive.

4.3. Limitations and future research

It is important to note that there are some limitations related to the adopted morphed weather data and the BPS tool in this study. Firstly, although the ensemble mean value of different climate change scenarios from 24 GCMs is used to consider the uncertainties between different scenarios and models, the morphed weather data represents only the typical weather conditions in the future. Also, due to the limits of BPS tools, the impacts of different urban morphology and the urban microclimate on the building energy performance have not been considered in our study. Therefore, uncertainties due to the future extreme weather conditions and synergy effect of urban heat island still remain to be examined. Nevertheless, though the current work focuses on the impacts of global climate change on residential buildings in Hong Kong, the results and recommendations are generally applicable for cities with similar hot and humid climates. As this study focused only on the impacts of future climate change on the energy saving effectiveness of passive design strategies, the detailed optimization and cost-benefit analyses for passive design strategies considering the changing climate would be worth investigating in future works. Additionally, the solar reflection and shadings from surrounding buildings in different urban morphologies and urban contexts which could cause the additional uncertainties for the results still need to be addressed in the future.

5. Conclusions

In this study, the newly developed future hourly weather data are employed for constructing the complete BBCC for Hong Kong under different climatic scenarios, and are then applied in building energy simulation tools to simulate the time-varying significance of various passive design parameters for the predominant residential buildings through a global SA. Results show that there will be a considerable increase in discomfort hours that will require cooling, from 2058 h in the TMY to 4106 h in RCP8.5–2090 s, even if the adaptive thermal model is applied as the thermal comfort criteria. Moreover, the effectiveness for different passive design strategies changes with different trends under the future changing climate. The significance of IFAC, i.e., building airtightness, is expected to increase up to 329% by the end of this century. Natural ventilation, achieved by using windows with a larger operable area, will continue to be an efficient way to cool the indoor thermal environment of residential buildings, but its cooling potential is significantly decreasing over time when the outdoor conditions become warmer. On the other hand, solar protection strategies and corresponding design parameters, such as SHGC, WSA and OPF, are recognized as highly sensitive strategies for building energy performance. However, there is a more dramatic decrease in effectiveness by these solar protection strategies when compared to envelope insulation, suggesting that the thermal mass

(Y-value) and insulation (U-value) of walls will become relatively more important for building energy performance in the future. After the different passive designs are implemented into the existing PRH residential buildings in TMY and RCP8.5–2090 s, results show that a holistic passive design can lead to an impressive effect in building energy saving. The annual and peak cooling load drops by 55.1% and 38.1% under the TMY climate scenario and 56.7% and 64.5% under the worst future climate scenario.

CRediT authorship contribution statement

Sheng Liu: Conceptualization, Investigation, Methodology, Visualization, Writing - original draft. **Yu Ting Kwok:** Conceptualization, Investigation, Writing - review & editing. **Kevin Ka-Lun Lau:** Conceptualization, Supervision, Funding acquisition. **Wanlu Ouyang:** Investigation, Visualization, Writing - review & editing. **Edward Ng:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is fully supported by the "Vice-Chancellor's Discretionary Fund" of the Chinese University of Hong Kong, Hong Kong and the "Research Impact Fund (Ref No: R4046-18F)" of Research Grants Council, Hong Kong.

Appendix

Tables A1–A3.

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