Reducing Energy Consumption and Improving Comfort by Retrofitting Residential Buildings in the Hot Summer, Cold Winter Zone of China

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Abstract

China's Hot Summer and Cold Winter zone with a 550 million population, accounts for 45% of China's building energy consumption; as such, building retrofits could offer substantial energy savings. This paper presents results from a dynamic thermal modelling study of a typical urban multi-storey residential building under three types of A/C operating schedules. Seven energy saving retrofit measures (external wall insulation, roof insulation, double-glazing, air infiltration control, window shading, communal staircase design and energy-efficient A/C) were evaluated, and the retrofit strategy with the highest annual energy savings and lowest thermal discomfort was identified. This retrofit strategy was subsequently evaluated for other flats (apartments) with different orientations and positions in the typical building. The annual space-conditioning energy could be reduced by 59 to 68%, depending on the flat location, orientation, and A/C operating schedule. The findings were then scaled up to estimate the potential energy savings in the city of Chongqing. Over 320 multi-storey residential buildings were represented by twelve archetypes. Space-conditioning energy consumption was reduced by up to 58% (18.8 TWh). This work provides evidence of the potential energy savings of city-scale retrofit that could aid China in reducing building energy consumption and achieving net-zero carbon emissions by 2050.

Practical applications

Using dynamic thermal models, it was possible to explore a wide range of refurbishment options for China's highly energy-consuming HSCW zone with hot, humid summers and mild, chilly winters. The simulation models developed in this paper revealed that double-glazing with air infiltration control is the most effective retrofit measure for middle-floor flats, but for top-floor flats, roof insulation is the most effective; south-facing flats consume more high energy consumption than north-facing flats. Furthermore, high-rise buildings consumed less energy than low-rise buildings per square meter, and one-bedroom flats consume more energy than three-bedroom flats per square meter. This study also demonstrated the procedure to develop thermal comfort evaluation methods, A/C operating schedules and construction parameters from literature in this climate zone, when there were no standards or databases available. Findings offer a tangible, clear retrofit strategy which considers different A/C operating schedules, flat locations, and building archetypes. It can assist decision making by practitioners and homeowners aiming to upgrade the building stock of this climate zone which covers 3.4billion m^2 with 550million population, so as to reduce energy consumption and improve occupant comfort.

Keywords: Residential buildings, China, retrofit, energy modelling, thermal comfort

1. Introduction

China is the second-largest economy in the world, contributing to 20% of the global energy consumptions (IEA, 2019), with the building sector accounting for 20% of the country's energy consumption (THUBERC, 2018). As living standards increase, the use of residential air conditioning (A/C) is steadily increasing (McNeil et al., 2016). Being the largest coal consumer (50% of the global coal consumption (Dudley, 2018), energy-efficient retrofits could reduce residential energy demand, enabling China to reduce total CO_2 emissions.

Out of the five climate zones in China, the Hot Summer and Cold Winter (HSCW) zone (Figure 1) contains 40% of China's population and is responsible for 45% of the country's building energy consumption (Xu et al., 2013). The urban domestic building stock in the HSCW zone covers around 3.4

billion m^2 and is occupied by 550 million people (NBS, 2017). Residential accommodation is typically high-rise apartment buildings consisting of single-family flats. The climate in this zone has considerable variations, with mean daily minimum temperatures of 0°C in winter and mean daily maximum temperatures of 30°C in summer (Li et al., 2014). According to China's design regulations, domestic space heating is only available to households in the cold and severe cold zones, excluding the HSCW zone (MOHURD, 2010a). As a result, indoor wintertime air temperatures in urban HSCW dwellings are between 5 and 15°C (Li et al., 2014) compared to those in the severe cold and cold zone, which range between 20 to 25°C. In the summer, indoor air temperatures in the HSCW dwellings can be up to 35°C (Li et al., 2014). These potentially uncomfortable temperatures have resulted in the widespread year-round use of low-efficiency air conditioners. Despite the consequential energy demands, only 2% of the HSCW residential building stock has been retrofitted since the introduction of the 2012 retrofit policy (State Council, 2012). The mandatory building regulation issued in 2010 (MOHURD, 2010a), intended to reduce the building energy consumption in the HSCW zone by 50%, but was focused on new builds.

Building energy modelling has been widely used to inform retrofit decisions. Previous studies typically evaluated individually selected retrofit measures (Ouyang et al., 2009; Wang et al., 2015; Yao, 2012; Yao et al., 2018) and then combined these into an optimum retrofit strategy to calculate energy savings; however, the thermal comfort improvements of the optimum retrofit strategies are often not considered alongside the energy savings. Moreover, previous studies (Li et al., 2018a; Short et al., 2018; Xu et al., 2013; Yao et al., 2018) have not compared predicted outputs from dynamic thermal models (DTMs) with measured data, which can lead to model/prediction discrepancies and less reliable estimates of energy-savings.

The typical A/C operating hours in Chinese households can vary significantly (Chen et al., 2011; Hu et al., 2013; Yoshino et al., 2006), significantly impacting energy consumption; however, previous retrofit studies in Chinese dwellings have focused on a single A/C operating schedule (Gou et al., 2018; Wang et al., 2015; Xu et al., 2013; Yu et al., 2008). Further, consideration should be given to different orientations and exposed wall/roof areas when predicting energy savings (Ouyang et al., 2009; Wang et al., 2015; Yao et al., 2018; Zhao et al., 2015). Studies by others have evaluated the effect of flat orientation (Short et al., 2018) and position of flats in buildings (Yao, 2012; Yu et al., 2008) on energy consumption, although not in combination.

When estimating building energy consumptions and the potential benefits of energy retrofits across a city, a bottom-up approach using building archetypes is deemed valuable (Reinhart and Cerezo Davila, 2016). Previous building energy studies focussed on the HSCW zone have developed archetypes based on building heights, surface-area-to-volume ratios and aspect ratios (Li et al., 2019, 2018a); but have not accounted for sensitive parameters such as the A/C operating schedule (Li et al., 2019) and the floor areas of individual flats (Hu et al., 2016).

This research holistically examines multiple factors that can influence energy consumption, including thermal comfort, different A/C operating schedules, and the effects of flat orientation and position on a typical building in the HSCW zone. This allowed for a city-scale retrofit study based in the city of Chongqing. To the author's knowledge, this has been the first parametric energy modelling study to explore how different A/C operating schedules, flat locations, and building archetypes influence energy demand predictions. The results will assist in reducing building energy consumption not only in the studied location but also in the broader HSCW zone in China, which is responsible for 45% of the country’s building energy consumption. By considering the building design, flat location, and a tangible, clear retrofit strategy, improvements in the household’s living standards can be made.

2. Methods

2.1. Overview

In the research reported here, the energy consumption for space heating and cooling and the thermal comfort of individual flats, single buildings and a city were predicted. The effect of seven energy saving retrofit measures was examined. Three different A/C operating schedules were also considered, representing different timings and durations of the summer and winter thermostat setpoint schedules.

A parametric study was conducted for the seven energy-saving retrofit measures. As a result, the most effective scenario for reducing energy consumption and improving thermal comfort was considered the optimum retrofit strategy at the flat scale.

A building scale analysis enabled the consideration of flats with different orientations and positions. The optimum retrofit strategy was applied to twelve flats across the typical building.

Twelve building archetypes were developed, considering buildings with different heights and flats with differing numbers of bedrooms. This allowed the evaluation of the selected optimum retrofit strategy across the city of Chongqing, through a city-scale study.

A representative area (3.4km^2) within the Yuzhong District in Chongqing, a major city in the HSCW zone, was selected for the city-scale study (Figure 2). The area has 334 (multi-storey) residential buildings, 95% (321) of which were built prior to the first building regulations (MOHURD, 2010a) and thus had poor building fabric. The total floor area of each of the 321 residential buildings was collected from building footprints shown on Baidu maps (Baidu, n.d.) multiplied by building height (field survey by Li et al., 2018a). In the representative area, 36% of residential buildings have ten or more storeys, and 50% have a building surface area to volume ratio between 0.15 and 0.25m^{-1}.

A typical building constructed in 1996, with ten storeys and a building surface area to volume ratio of 0.188m^{-1} was selected for the building scale study. It had eight residential floors (twelve one-bedroom flats per floor, 96 in total) and two lower floors for commercial use (Figure 3). A flat on the second floor, centred on the main façade facing 30° to the East of true North, described as flat MCF in Figure 3, was selected for the flat-scale study. It consists of a living room, bedroom, kitchen and toilet (Figure 4). The building selected was one of the most predominant out of 321 residential buildings in the representative area. The flat selected was a centred middle floor flat, which represented over half (58%) of flats in the typical building.

The methodology used in this study is summarised in Figure 5. Using the case study flat, multiple options were evaluated for each of the seven energy-saving retrofit measures, using a total of 25 simulations. The most effective scenario for reducing the total (heating plus cooling) space-conditioning energy consumption and annual hours of thermal discomfort was determined. This was then applied to twelve flats with different orientations and positions within the case study building. Analysis was undertaken for three A/C operating schedules - a total of 36 simulations. Lastly, twelve archetypes, combined with three A/C operating schedules were used to predict the city-scale energy consumption reduction for the Yuzhong District of Chongqing.

2.2. Dynamic thermal model description

DesignBuilder (v6.1.2.009) based on EnergyPlus (v8.9) was used to model the case study building using the Typical Meteorological Year (TMY) for Chongqing (EnergyPlus, 2021). Table 1 summarises the weather data for mean monthly dry-bulb temperature and relative humidity for Chongqing. The mandatory building regulation issued in 2010 (MOHURD, 2010a) defined thermal properties such as equipment power density and lighting density, which were used in the models (Table 2). However, the U-values defined in the regulation were applicable to new builds (buildings constructed after 2010), and thus were not used in this study. Thus, due to the lack of construction information for the case study building, building parameters were defined empirically using information from others and collected during a site visit by the authors (11/2015). Table 2 and Table 3 present the building parameters and the properties of construction materials, respectively. Literature showed that residential buildings in the HSCW zone have poor to very poor air infiltration performance, e.g. 1ach^{-1} (Yu et al., 2013, 2008) to 2ach^{-1} (Li et al., 2019, 2018a and McNeil et al., 2016). An average value of 1.5ach^{-1} was adopted in this study.

During A/C operation, the windows were assumed to be closed, as 82% of households in the HSCW zone close the windows when they operate A/C (Hu et al., 2017). However, when A/C was switched off, the windows were opened for outdoor temperatures above 17°C, according to Liu et al. (2017). The ventilation rate during window operation is calculated using equation 1, taken from CIBSE Guide A, for estimating single-sided ventilation rates (CIBSE, 2015).

$$Q = 0.025 \times A \times u \qquad (1)$$

where Q is the volumetric flow rate through the opening (m^3/s), A is the area of the opening (m^2), u is the wind velocity ms^{-1}.

The A/C system was selected according to a study showing that 47% of households in China use a split type A/C system with a rated cooling capacity below 4.5kW and heating and cooling coefficients of performance (COPs) of 2.2 and 2.6, respectively (Yu et al., 2015).

Internal heat gains were defined for the periods shown in Figure 6 and consisted of lighting, equipment, and people gains. It was assumed that the kitchen was occupied between 18:00-19:00 for cooking, with internal heat gains of 10.8W/m^2 (after Yu et al., 2008). Lighting gains were 6W/m^2 and equipment 4.3W/m^2 as per the Chinese lighting and design standards (MOHURD, 2013, 2010a). Metabolic rates per person were 90W in the bedroom from 23:00 to 06:00 and 123W in the living room between 17:00 and 23:00 (ASHRAE, 2018). As the average living area per person in Chongqing was 29.3m^2 (NBS, 2017), two occupants were assumed per flat, with heat gains of 6.6W/m^2.

Three types of A/C operating schedules were created to represent the main types of occupants and their energy usage (Figure 6). The A/C operating hours were defined according to survey outputs from literature (Chen et al., 2015, 2011; Hu et al., 2013; Lin et al., 2016; Yoshino et al., 2006), providing hourly A/C operating schedule percentages for a typical day. Heating and cooling setpoints for the living spaces were defined to be 17.7°C in winter and 27.9°C in the summer, as observed in previous studies (Li et al., 2018b), which are 0.3°C lower in winter and 1.9°C higher in summer than those suggested by building standards (MOHURD, 2010a).

Winter discomfort was defined as an indoor air temperature below 17.7°C (Li et al., 2018b), and summer discomfort as an indoor air temperature exceeding 27.9°C. The annual occupied hours of thermal discomfort in the bedroom and the living room were calculated, and the sum of the two was taken as the total annual hours of thermal discomfort. For a relative humidity comfort range of 30%-80% in the HSCW zone (Li et al., 2018b), a relatively high level of RH (70%) was assumed consistently in this study.

To increase the reliability of predictions, the developed DTM was verified by comparing predicted hourly indoor air temperature with measured indoor air temperature data collected for one week in April 2018. The authors have previously published the details of this work in Tsang et al. (2018). This approach was similar to that adopted by others, such as Short et al. (2018), where indoor air temperature data were collected for one week in January and one week in August. For the research reported here, a single week of measured data was available to verify the model, and thus this rather short verification period is one of the limitations of this work.

As a benchmark, previous studies (Chen et al., 2013, 2011; Hu et al., 2013; and Ouyang et al., 2011, 2009) have quoted the annual energy consumption of un-retrofitted Chinese flats as: heating, 2.2 to 7.42kWh/m^2; cooling, 2.69 to 10.32kWh/m^2; and total, 7.67 to 16.92kWh/m^2.

2.3. Selection of retrofit measures

Fourteen retrofit measures, typically employed for residential building retrofits in the HSCW zone, were identified from previous studies (Li et al., 2019; Ouyang et al., 2009; Short et al., 2018; Yao et al., 2018; Yu et al., 2008), are summarised in Table 4. From these, only passive measures that require no occupant control (e.g., curtains/blinds/shutters etc.) were considered, and therefore, seven retrofit measures were selected (Table 4). In addition, due to the lack of retrofit regulations for residential buildings built before 2010, a list of retrofit options for each of the seven retrofit measures was developed empirically using information from other studies, summarised in Table 5.

Retrofit-1: External wall insulation

The existing external wall (U-value 2.3W/m^{2}K) was insulated with expanded polystyrene (EPS), which, according to findings by Liu et al. (2015), is the most economical external wall insulation material for residential buildings in the HSCW zone. Five thicknesses of EPS insulation were evaluated, ranging from 10 mm (U-value = 1.3W/m^{2}K) to 30 mm (U-value 0.7W/m^{2}K).

Retrofit-2: Roof insulation

EPS insulation was selected as an effective and economical solution for the currently uninsulated roof, which had a high U-value (3.45W/m^{2}K) (Yu et al., 2011). Four insulation thicknesses were evaluated, from 20mm (U-value 1.31W/m^{2}K) to 50mm (U-value 0.65W/m^{2}K). Roof insulation was not tested for flats that were not on the top floor.

Retrofit-3: Double-glazed windows

Five typical types of double-glazed windows were identified in literature to replace the existing single-glazed windows (U-value 5.8W/m^{2}K, SHGC 0.87). These ranged from standard (6/12/6) double glazing with an air-filled cavity and aluminium frames (U-value 3.9W/m^{2}K, SHGC 0.85) to double, low-emissivity glazing (6/12/6) with an argon-filled cavity and UPVC frames (U-value 1.5W/m^{2}K, SHGC 0.54).

Retrofit-4: Air infiltration control

Chinese building regulations suggest an infiltration rate of 1.0ach^{-1} for new residential buildings (MOHURD, 2010a) and a minimum of 0.5ach^{-1} to avoid the need for mechanical ventilation (Fu et al., 2017). Accordingly, infiltration rates form 1.0ach^{-1} to 0.5ach^{-1} were considered.

Retrofit-5: Window shading

Yu et al. (2008) tested overhang lengths from 0.3 to 1.5m and found that the energy savings diminished for overhang lengths of 1.0 to 1.5m. Therefore, three overhang lengths were considered, 0.3m, 0.5m and 1.0m.

Retrofit-6: Communal staircase design

The communal staircase of the case study building was exposed to outdoor conditions; this is typical of multi-storey buildings in the representative area of Chongqing. Previous DTM studies included the floor area of the communal corridors within the living space floor area, influencing the reliability of predicted energy savings (Ouyang et al., 2011, 2009). Here, the outdoor communal corridor was changed from external to internal but not included in the simulated living space floor area (Figure 7).

Retrofit-7: Energy-efficient A/C

Three different grades of A/C systems were selected based on the Chinese regulations governing room A/C energy efficiency grades (MOHURD, 2010b). The least efficient, Grade 3, had COPs of 2.7 and 3.2 for heating and cooling respectively, and the most efficient (Grade 1) COPs of 3.1 for heating and 3.6 for cooling.

Retrofit-2 was tested on a central top floor flat (flat TCF) and the other six measures on a middle floor central flat (flat MCF) and the TCF. For each of the seven retrofit measures (Table 5), the most effective option for reducing energy consumption and improving thermal comfort conditions was predicted for the case study flat assuming the medium A/C operating schedule (Figure 6). When modelling an individual retrofit measure, all other parameters were kept at the base case values (Table 5). For each retrofit option, the energy savings and thermal discomfort were compared with the corresponding base case values. The best performing variant of each retrofit measure was identified.

2.4. Building scale evaluation

To allow customisation of retrofit measures and to optimise performance across the different types of flats, twelve flat categories were identified with different orientations and on different floors (Figure 3). All remaining spaces were assumed to be adiabatic blocks for the simulation work (i.e., there was no heat exchange between them and the modelled flat). The optimum retrofit strategy was applied to each of the twelve flats and modelled for each of the three A/C operating schedules, a total of 36 simulations.

2.5. City scale dynamic thermal model

Building archetypes, which are statistical composites of the features found within a category of building in a city, were created to model the effect of city-scale energy-saving retrofits. Previous studies by Hu et al. (2016) and Li et al. (2019) were also used to inform the archetypes' development. The total floor area of each of the 321 residential buildings was collected from building footprints shown on Baidu maps (Baidu, n.d.) and the building heights through a field survey by Li et al. (2018a). Twelve archetypes were developed with 3, 5, 8 or 16 number of storeys, and 1, 2 or 3 number of bedrooms per flat, which accounted for the variation of building types in the representative area of Chongqing. Energy models were created for each archetype, combined with the three A/C operating schedules, leading to a total of 36 DTM simulations performed (Figure 8). Heating and cooling energy consumption was predicted for each case.

To model the archetypes, building-specific details, e.g., bay windows, were removed (Figure 9) to widen the applicability of the findings. In addition, only flats MCF and TCF were modelled (Figure 3) as ancillary studies showed that modelling all flats only changed the building energy consumption by 1% (Tsang, 2020).

Single bedroom households in Chongqing account for 24%, two-bedroom 42%, and 34% of households have three or more bedrooms (NBS, 2010). In the archetypes, it was presumed that these proportions prevailed in each building irrespective of the building height. The one-bedroom flats were assumed to have equal floor area to the case study flat, and the two- and three-bedroom archetypes were derived from the mean floor area of previous studies (Ichinose et al., 2017; Short et al., 2018; Yao, 2012; Yu et al., 2008), all listed in Table 6.

The urban residential building stock in the HSCW zone is classified into four types with regard to the number of storeys (MOHURD, 2005): low-rise (one to three floors); middle-rise (four to six floors); middle high-rise (seven to nine floors); and high rise (ten and above). In the representative area, 10% are low-rise buildings (31 buildings), which had an average number of storeys of 2.5, and thus a three-storey building was modelled to represent low-rise buildings. Similarly, 16% are medium-rise buildings (average storeys 5.2) and a five-storey building was modelled, 38% are middle high-rise buildings (average storeys is 8.1) and an eight-storey building was modelled, and 36% are high-rise buildings (average storeys 16.2) and a 16-storey building was modelled.

The total floor area for each of the 321 residential buildings was collected, and the area of the unconditioned communal corridor, which represents 14% of the total (Short et al., 2018; Yao et al., 2018; Yu et al., 2008) was excluded. The conditioned floor area was 1530m^2 for low-rise buildings, 3050m^2 for medium-rise buildings, 7120m^2 for medium high-rise buildings, and 19200m^2 for high-rise buildings (Table 7). The total space heating and cooling energy consumption of the representative area was predicted by multiplying the specific energy consumption (kWh/m^2) by the floor area of each archetype.

3. Results

3.1. Pre-retrofit energy and thermal comfort performance – case study flat

The pre-retrofit space conditioning energy consumption of the case study flat (flat MCF) was selected as the base case scenario. The predicted space-conditioning energy consumption was within the ranges provided by others (Chen et al., 2013, 2011; Hu et al., 2013; Ouyang et al., 2011, 2009). The annual energy consumption for the three different A/C operating schedules varied significantly (Table 8), with low A/C operating schedule consuming half the energy of high A/C operating schedule. The annual energy consumption ratio for heating and cooling was about 40:60 for all three A/C schedules, which is in line with previous studies which suggested ratios between 30:70 and 50:50 (Hu et al., 2013; Ouyang et al., 2011).

In the living room, winter discomfort was predicted to be 941h, and summer discomfort 736h, with total annual discomfort of 1677h, which is 57.4% of the occupied hours (2555 in the bedroom and 2920 in the living room). In the bedroom, winter discomfort hours were predicted to be 869h, and for summer discomfort 570h, which is 56.4% of occupied hours. Thus, the predicted discomfort is in line with the discomfort hours of 55% provided by others' surveys (Li et al., 2018b, 2014).

3.2. Effect of retrofit on energy consumption and comfort – case study flat

The heating, cooling and total space conditioning energy consumption for each retrofit option are presented below, along with the winter, summer, and annual discomfort hours. The results are expressed relative to the base-case flat in Figure 9.

<u>Retrofit-1: External wall insulation</u> resulted in small energy consumption reductions (Figure 10a). The total energy reduction with 30mm EPS insulation (U-value = 0.7W/m^{2}K) was just 2.9% less than the base case, and the annual occupied hours of discomfort was just 37 less. Heating energy was reduced

by 5%, and cooling energy was increased by 1% when compared to the base-case. The external wall of the flat adjacent to the communal staircase was not insulated as it would subtract the spaces of the communal staircase, which has been sized based on local regulations. Therefore, external wall insulation resulted in the lowest energy reduction, as it only insulated part of the external wall of the case study building.

Retrofit-2: Roof insulation was assessed for the top floor flat (TCF). The best performing retrofit option was 50mm of EPS roof insulation (U-value 0.65 W/m^{2}K), with a total energy reduction of 27%, although just 20mm of EPS insulation gave a reduction of 22% (Figure 10b). Of all the retrofit options, roof insulation offered the greatest reduction in thermal discomfort. The reduction in discomfort increased as the insulation level increased. With 50mm of EPS, the total hours of thermal discomfort reduced by 320, most notably because winter cold discomfort was reduced.

Retrofit-3: Double-glazed windows of all types offered heating, cooling and total energy consumption reductions. The total energy reduction was up to 15.7%, and the cooling energy reduction was up to 24% (Figure 10c). As expected, a lower SHGC (0.54) resulted in a greater cooling energy consumption reduction even though the heating energy saving was less. A lower SHGC also resulted in a reduction in thermal discomfort, primarily because summer thermal discomfort was reduced (by up to 140h). Changes in the window U-value had only a small impact on thermal discomfort and the total energy consumption. The total and heating energy saving increased a little as the U-value decreased.

Retrofit-4: Air infiltration control resulted in a marked reduction in the heating energy consumption, up to 31% reduction at 0.5ach^{-1}. The change in the summer cooling energy consumption was small, resulting in an overall annual energy saving of 14% (Figure 10d). The lower infiltration rates had little effect on the total annual hours of discomfort, but the increase in the summertime hours of thermal discomfort at lower air infiltration rates could easily be offset by increasing the increased window opening.

Retrofit-5: Window shading reduced the annual energy consumption by up to 6% as a result of a heating energy increase of 2% and a cooling energy reduction of 11.5% (Figure 10e). The overall reduction of annual thermal discomfort was small, just 17h, with up to 52h of reduced summertime discomfort being offset by greater winter thermal discomfort.

Retrofit-6: Enclosing the communal staircase, which was previously open, performed better than without the enclosing (Figure 10f), achieving reductions of total energy consumption of 10% and total thermal discomfort hours of 68h.

Retrofit-7: Energy-efficient A/C offered up to a 28% reduction in annual energy consumption (Figure 9g). The thermal discomfort hours remain unchanged as the setpoint temperatures and A/C operating schedule remained the same as for the base case building.

Of the six retrofit options that are applicable to the case study flat (MCF), the summer, winter and annual energy reductions were all greatest if the energy efficiency of the air-conditioning system was improved, followed by installing double glazed windows with a low-SHGC (Figure 11a).

Accordingly, an optimum retrofit strategy was devised to combine the most effective measures: external wall EPS insulation of 30mm; new double-glazed low-e window with solar control; air infiltration rate of 0.7ach^{-1}; new overhang with 0.5m length; enclosed indoor communal staircase; and new Grade 1 energy-efficient rating air-conditioners. The selected optimum retrofit strategy when applied to the case study flat reduced the total energy consumption by 60% (73% for heating and 52% for cooling) (Figure 11a). In addition, the optimum retrofit strategy was also effective in reducing thermal discomfort by 343h in winter with only a small increase (10h) in summer (Figure 11b).

3.3. Optimum combined retrofit strategy at building scale

3.3.1. Pre-retrofit energy performance across different flats

Pre-retrofit energy consumption varied significantly for different flat locations relative to the case study flat (flat MCF) (Figure 12). An eighth of the building's flats are on the top floor and subjected to higher heat losses. Thus, flat TCF, was predicted to have 89% higher heating energy consumptions and 35% higher cooling consumptions compared to a central, middle floor flat (MCF) with the same orientation (Figure 12). Half of the building's flats are facing N30°E (Front) and the other half S30°W (Rear); this

180° orientation difference, for otherwise identical flats, leads to significant heating and cooling load variations. This was particularly evident for flat MCR which, when facing S30°W, was predicted to have 12.3% lower heating energy consumption and 21.8% higher cooling energy consumption, compared to flat MCF facing N30°E. This is due to the higher solar gains, which increased cooling energy but decreased heating energy. The total energy consumptions across the eight floors and the two different façade orientations varied significantly for the three types of A/C operating schedules (Figure 12).

3.3.2. Combined retrofit strategy for different flats

When the optimum retrofit strategy was employed across different flats, the change in energy consumption between the various flats was quite similar, for the low A/C operating schedule, 59 to 69%, medium operating schedule, 60 to 66%, and high operating schedule, 62 to 68% (Figure 13a). Yet, the absolute value of energy reduction (in kWh/m^2) varied significantly by flat location (Figure 13b). For example, flat MCF had the smallest absolute total annual energy consumption reduction ($7.33kWh/m^2$) and flat TLR the greatest ($13.24kWh/m^2$) due to its larger area of exposed walls and roof, along with south facing windows.

With medium A/C operating schedule, the pre-retrofit total energy consumption of top floor flat TCF was 60% higher than a middle floor flat MCF. Post-retrofit, the total energy reduction for flat TCF was 66%, 6% more than MCF. The absolute energy reduction for flat TCF ($12.5kWh/m^2$) was also much greater than flat MCF ($7.3kWh/m^2$). Flats facing the rear S30°W were predicted to have 3% higher total energy consumption reduction than flats facing the front N30°E, but the absolute energy reduction was only $0.9kWh/m^2$ higher for flat MCR than flat MCF.

The energy-saving retrofits offered significant reductions in winter thermal discomfort (from 283 to 394h) and summer discomfort (5 to 117h) for all flats except MCF, which had just 10h more summer discomfort (Figure 13c). For top floor flats, e.g., TCF, winter and summer discomfort h reduced substantially (by 364h and 66h, respectively). For rear facing flats, S30°W, the annual discomfort hours reduction was 71h more than that of front facing flats, N30°E.

Overall, the combined optimum retrofit strategy substantially reduced the wintertime heating consumptions and the summertime cooling consumptions for all A/C operating schedules. The incidence of wintertime cold thermal discomfort was also reduced without increasing the incidence of summertime warm discomfort.

3.4. Large scale energy-saving retrofits using residential building archetypes

3.4.1. Combined retrofit strategy – residential building archetypes

The pre-retrofit heating energy consumption of the twelve typical residential building archetypes varied between 2.87 and 5.93kWh/m^2 and the cooling consumption between 7.11 and 8.01kWh/m^2 (Figure 14). Total energy consumption pre-retrofit was about 10% higher per square metre in low-rise buildings (3F, 12.5kWh/m^2 averaged energy consumption) than in high-rise buildings (16F, 11.2kWh/m^2 averaged energy consumption). These results are in accordance with findings by Li et al. (2018a), in which energy consumption was predicted to be 5% higher for a lower rise (8-storey) than a higher rise (26-storey) building. This result is because top floor flats may consume about 60% more heating energy than middle floor flats, and lower buildings having a larger percentage of top floor flats (33% in three-storey) relative to higher buildings (6% in 16-storey).

Total energy consumption was about 20% higher per square meter for flats with fewer bedrooms (1B, 13.1kWh/m^2 averaged total energy consumption) than for flats with more bedrooms (3B, 10.4kWh/m^2 averaged total energy consumption). This is primarily because of the longer A/C operating hours in living rooms compared to bedrooms. The total energy consumption was, as expected, greater for high A/C operating schedule (14.1 to 18kWh/m^2 for the twelve archetypes) than for low A/C operating schedule (6.5 to 9.9kWh/m^2).

3.4.2. City scale energy-saving retrofits

The predicted pre-retrofit heating and cooling energy consumption for the 321 residential buildings was 30.9TWh for medium A/C operating schedule (Figure 15), which is about 40% more than the consumption for low A/C operating schedule and 30% less than for high A/C operating schedule. When the optimum retrofit strategy was employed, energy consumptions were reduced to 10.9TWh, 14.6TWh and 19.5TWh, for the low, medium and high A/C operating schedules respectively, representing a saving of 55%, 59% and 62%.

Assuming that the three types of A/C operating schedules are equally distributed across the households in the 321 multi-storey residential buildings, the predicted pre-retrofit total energy consumption was 32.3TWh (12.1kWh/m^2), and the optimum retrofit achieved a 58% (18.7TWh) total energy reduction. As living standards are expected to increase in the future, the usage of A/C in the HSCW zone might also increase. If all occupants in the representative area used the high A/C operating schedule, the predicted energy consumption would reduce by 45% from the pre-retrofit value of 44TWh to a post-retrofit value of 19.5TWh.

4. Discussion

The Chinese design standard (MOHURD, 2010a) lists mandatory design conditions for newly built dwellings but missed to offer advice for retrofitting existing buildings; the energy-saving retrofits evaluated in this study can be used as retrofit guidance. This study suggests use of lower U-values compared to the Chinese standards for external walls (0.79 compared to 1.0W/m^2K) and windows (1.9 compared to 2.8W/m^2K); also, having double-glazed windows and enclosed communal staircases reduces air infiltration rates from 1.5 to 0.7ach^{-1}, whereas the Chinese design standard mandates 1.0ach^{-1}. Additional measures examined are limiting the SHGC of windows to 0.54 and installing a horizontal overhang with a length of 0.5m to reduce summer solar heat gains. The predicted energy savings for a typical city area using the higher energy efficiency standards proposed here were reduced by 58%, which indicates that large scale retrofit could substantially reduce domestic energy demand in the HSCW zone of China.

The three tiers of A/C operating schedules adopted in this work delivered predicted pre-retrofit annually energy consumptions ranging from 9.2 to 16.4kWh/m^2 for the case study flat. These were less than half of the values predicted by other studies (24.9-44kWh/m^2) but were closely aligned with data collected in 882 flats by energy suppliers (7.7-16.9kWh/m^2) (Chen et al., 2013, 2011, 2010; Hu et al., 2013; and

Ouyang et al., 2011). The heating setpoint used was lower (by 0.3°C), and the cooling higher (by 1.9°C) than the recommended by the Chinese standards (MOHURD, 2010a), which leads to the lower predictions of heating and cooling energy consumption.

In comparison with the results of others, this research indicates lower energy savings. External wall insulation offered 4% energy reductions, 2% less energy reductions relative to those reported by Ouyang et al. (2009), for the same insulation thickness. Air infiltration control delivered 12% total energy reduction compared to 25% for the same air infiltration control reported by Zhao et al. (2015), possibility due to assuming 24-hour A/C operation rather than 5 hours for heating and 8 hours for cooling as used in this work, which was based on occupant surveys (Chen et al., 2011, 2010; Hu et al., 2013; Yoshino et al., 2006). Enclosing previously external communal staircases, is the least investigated retrofit measure in literature; yet it was shown in this work to offer 10% total energy reduction.

The thermal comfort evaluation method were developed with regards to a number of surveys reported in the literature (Li et al., 2018b, 2014). These surveys showed that over half of the year (55%) occupants are uncomfortable (indoor air temperature in winter below 17.7°C and summer above 27.9°C). This study predicted 56.4% hours of thermal discomfort during occupied hours, whereas studies by others predicted thermal discomfort during occupied hours of 75-80% (Gou et al., 2015; Li et al., 2014; Yao et al., 2018). For instance, Yao et al. (2018) predicted 78% of thermal discomfort occupied hours, for indoor air temperature 18-26°C (as defined according to the Chinese design standard).

A 60% higher total energy consumption for top floor flats (flat TCF) compared to a flat in the middle of the building (MCF) was predicted; previous studies missed to evaluated the effect of top floor flats for residential buildings in the HSCW zone. Moreover, 10% higher total energy consumption was predicted for middle corner flats (MLF and MRF) compared to the middle flat (MCF), which is similar to others' predictions, of 10% higher (Yao 2012) and 15% higher (Yu et al., 2008). Likewise, a 12% increase in total energy consumption was predicted for flats facing S30°W compared to a flat facing N30ºE, which is more than the 6% suggested by Short et al. (2018).

Twelve residential building archetypes were used to represent residential buildings in Chongqing, compared to previous studies using just three archetypes of varying building heights (Li et al., 2018a) or five archetypes with a varying number of bedrooms (Li et al., 2019). The archetypes created here allowed for higher accuracy of predictions, compared to those devised by Li et al. (2019), which assumed 50% bedroom area of the entire flat irrespective of the number of bedrooms (one to three); leading to similar predicted energy consumption across flats of different floor area. The aggregated energy consumption in the representative area of Chongqing was predicted to be 11.32kWh/m^2 (32.3TWh) pre-retrofit. The findings are in contrast to Li et al. (2018a), where the predicted energy consumption was three times greater (37.64kWh/m^2), but Li et al. (2018a) used a generalised, single A/C operating scenario.

The sources of uncertainty in this study were the modelling assumption used in Table 2. Ancillary studies performed by Tsang et al. (2018) and Tsang (2020) investigated the uncertainty of modelling assumptions in Table 2 by varying the base-case input to a higher and lower value. Results showed that the air infiltration rate was the largest source of uncertainty, values varied from 1 to 2ach^{-1}.

There are limitations to this study. For example, it only explores a few of the potential retrofit measures and does not consider the impact of humidity on energy demand and thermal comfort. Also, the actual orientation of 321 residential buildings was not considered, as the archetypes were assumed to have North orientation, this limitation may impact the accuracy of results; a 2-12% underestimation of the total energy consumption for flats facing N30°E compared to S30°W was predicted during the orientation study of the case study building. Future work could also consider different climates within the HSCW zone and whether the optimal retrofit is climate sensitive.

5. Conclusion

This study examined the annual heating and cooling energy consumption and the annual thermal discomfort of existing residential buildings in the hot summer, cold winter (HSCW) zone of China. Seven different retrofit measures were evaluated, and an optimum retrofit strategy was identified for flats in a typical residential building in Chongqing. A city-scale study evaluated the impact on heating and cooling energy consumption and year-round thermal comfort of an optimum retrofit strategy for a representative area in Chongqing.

The principal findings from this study, for the chosen individual flat, are:

- Replacing single glazing with low-emissivity double-glazing reduced the total energy consumption for space conditioning by 15%, and led to 70 fewer annual discomfort hours;
- Double-glazing with air infiltration control offered 30% total energy savings, and 70 fewer annual discomfort hours;
- Roof insulation achieved 28% total energy savings and 325 fewer annual discomfort hours for top floor flats;
- Enclosing the communal staircase was an effective retrofit measure, achieving 10% total energy savings and 68 fewer annual discomfort hours;
- External wall EPS insulation is the least effective measure contributing to only 3% of total energy savings and 35 fewer annual discomfort hours;
- When all the retrofit measures were combined, 60% total energy consumption reduction and 320 fewer annual discomfort hours were achieved.

Top floor flats had 60% higher energy consumption than middle floor flats prior to retrofit, and south-facing flats had 8% higher energy consumption than north-facing flats. The energy reduction achieved across twelve flats, with different orientations and positions, varied between 60% and 67% for the optimal retrofit strategy.

The city-scale modelling revealed that high-rise buildings consumed 10% less energy (kWh/m^2) than low-rise buildings, while buildings with one-bedroom flats consume 20% more energy (kWh/m^2) than those with three-bedroom flats. Across the 321 buildings in the representative area in Chongqing, the optimum retrofit strategy saved between 54% and 65% of the annual energy consumption for heating and cooling.

It is clear that the retrofit of existing residential buildings in the HSCW region of China can reduce heating and cooling energy demand and reduce thermal discomfort, especially in winter. Such retrofit would benefit the 550 million people living in the HSCW region and help the country reduce its reliance on fossil fuels so reducing CO_2 emissions.

Data Availability Statement

All data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgements

This work was undertaken as part of the collaborative China-UK project, Low carbon climate responsive Heating and Cooling of cities (LoHCool), funded by the UK Engineering and Physical Sciences Research Council (EP/N009797/1). The project is a collaboration between Cambridge, Reading and Loughborough Universities and the Universities of Chongqing and Hangzhou in China.

References

ASHRAE, 2018. ASHRAE handbook fundamentals. ASHRAE standard. American Society of Heating Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia.

Baidu, n.d. Baidu Maps [online] Available through: <https://map.baidu.com> [Accessed 1 Novemeber 2021].

Chen, J., Wang, X., Steemers, K., 2013. A statistical analysis of a residential energy consumption survey study in Hangzhou, China. *Energy and Buildings*, *66*, 193–202.

Chen, S., Li, N., Yoshino, H., Guan, J., Levine, M.D., 2011. Statistical analyses on winter energy consumption characteristics of residential buildings in some cities of China. *Energy and Buildings*, *43*, 1063–1070.

Chen, S., Yang, W., Yoshino, H., Levine, M.D., Newhouse, K., Hinge, A., 2015. Definition of Occupant Behavior in Residential Buildings and Its Application to Behavior Analysis in Case Studies. *Energy and Buildings*, *104*, 1–13.

Chen, S., Yoshino, H., Li, N., 2010. Statistical analyses on summer energy consumption characteristics of residential buildings in some cities of China. *Energy and Buildings*, *42*, 136–146.

CIBSE, 2015. CIBSE Guide A: Environmental design. The Chartered Institution of Building Services Engineers, London, UK.

Dudley, B., 2018. BP Statistical Review of World Energy. London: BP plc.

EnergyPlus, 2021. Weather Data [WWW Document]. URL https://energyplus.net/weather (accessed

1.20.06).

Fu, X., Qian, X., Wang, L., 2017. Energy efficiency for airtightness and exteriorwall insulation of passive houses in hot summer and cold winter zone of China. *Sustainability (Switzerland)*, *9*.

Gao, Y., Xu, J., Yang, S., Tang, X., Zhou, Q., Ge, J., Xu, T., Levinson, R., 2014. Cool roofs in China: Policy review, building simulations, and proof-of-concept experiments. *Energy Policy*, *74*, 190–214.

Ge, J., Wu, Jiajing, Chen, S., Wu, Jindong, 2018. Energy efficiency optimization strategies for university research buildings with hot summer and cold winter climate of China based on the adaptive thermal comfort. *Journal of Building Engineering*, *18*, 321–330.

Gou, S., Li, Z., Zhao, Q., Nik, V.M., Scartezzini, J.L., 2015. Climate responsive strategies of traditional dwellings located in an ancient village in hot summer and cold winter region of China. *Building and Environment*, *86*, 151–165.

Gou, S., Nik, V.M., Scartezzini, J.L., Zhao, Q., Li, Z., 2018. Passive design optimization of newly-built residential buildings in Shanghai for improving indoor thermal comfort while reducing building energy demand. *Energy and Buildings*, *169*, 484–506.

Hu, S., Yan, D., Cui, Y., Guo, S., 2016. Urban residential heating in hot summer and cold winter zones of China-Status, modeling, and scenarios to 2030. *Energy Policy*, *92*, 158–170.

Hu, S., Yan, D., Guo, S., Cui, Y., Dong, B., 2017. A survey on energy consumption and energy usage behavior of households and residential building in urban China. *Energy and Buildings*, *148*, 366–378.

Hu, T., Yoshino, H., Jiang, Z., 2013. Analysis on urban residential energy consumption of Hot Summer & Cold Winter Zone in China, Sustainable Cities and Society.

Ichinose, T., Lei, L., Lin, Y., 2017. Impacts of shading effect from nearby buildings on heating and cooling energy consumption in hot summer and cold winter zone of China. *Energy and Buildings*, *136*, 199–210.

IEA, 2019. World Energy Outlook 2019 [WWW Document]. URL https://www.iea.org/reports/world-energy-outlook-2019 [Accessed 1 November 2021]

Li, B., Yao, R., Wang, Q., Pan, Y., 2014. An introduction to the Chinese Evaluation Standard for the indoor thermal environment. *Energy and Buildings*, *82*, 27–36.

Li, X., Yao, R., Liu, M., Costanzo, V., Yu, W., Wang, W., Short, A., Li, B., 2018a. Developing urban residential reference buildings using clustering analysis of satellite images. *Energy and Buildings*, *169*, 417–429.

Li, B., Du, C., Yao, R., Yu, W., Costanzo, V., 2018b. Indoor thermal environments in Chinese residential buildings responding to the diversity of climates. *Applied Thermal Engineering*, *129*, 693–708.

Li, X., Yao, R., Yu, W., Meng, X., Liu, M., Short, A., Li, B., 2019. Low carbon heating and cooling of residential buildings in cities in the hot summer and cold winter zone - A bottom-up engineering stock modeling approach. *Journal of Cleaner Production*, *220*, 271–288.

Lin, B., Wang, Z., Liu, Y., Zhu, Y., Ouyang, Q., 2016. Investigation of winter indoor thermal environment and heating demand of urban residential buildings in China's hot summer - Cold winter climate region. *Building and Environment*, *101*, 9–18.

Liu, H., Wu, Y., Li, B., Cheng, Y., Yao, R., 2017. Seasonal variation of thermal sensations in residential buildings in the Hot Summer and Cold Winter zone of China. *Energy and Buildings*, *140*, 9–18.

Liu, X., Chen, Y., Ge, H., Fazio, P., Chen, G., 2015. Numerical investigation for thermal performance of exterior walls of residential buildings with moisture transfer in hot summer and cold winter zone of China. *Energy and Buildings*, *93*, 259–268.

McNeil, M.A., Feng, W., de la Rue du Can, S., Khanna, N.Z., Ke, J., Zhou, N., 2016. Energy efficiency outlook in China's urban buildings sector through 2030. *Energy Policy*, *97*, 532–539.

MOHURD, 2013. GB 50034-2013: Standard for lighting design of buildings (in Chinese). Beijing, China.

MOHURD, 2010a. JGJ 134-2010: Design standard for energy efficiency of residential buildings in Hot Summer and Cold Winter zone (in Chinese). Beijing, China.

MOHURD, 2010b. GB 12021.2-2010 :The minimum allowable values of the energy efficiency and energy efficiency grades for room air conditioners (in Chinese). Beijing, China.

MOHURD, 2005. GB 50352-2005: Code for Design of Civil Buildings (in Chinese). Beijing, China.

NBS, 2017. China Statistical Yearbook 2017 (in Chinese). Beijing, China.

NBS, 2010. National Bureau of Statistics of People's Republic of China on Major Figures of the 2010 Population Census (in Chinese). Beijing, China.

Ouyang, J., Ge, J., Hokao, K., 2009. Economic analysis of energy-saving renovation measures for urban existing residential buildings in China based on thermal simulation and site investigation. *Energy Policy*, *37*, 140–149.

Ouyang, J., Wang, C., Li, H., Hokao, K., 2011. A methodology for energy-efficient renovation of existing residential buildings in China and case study. *Energy and Buildings*, *43*, 2203–2210.

Reinhart, C.F., Cerezo Davila, C., 2016. Urban building energy modeling - A review of a nascent field. *Building and Environment*, *97*, 196–202.

Short, C.A., Song, J., Mottet, L., Chen, S., Wu, J., Ge, J., 2018. Challenges in the low-carbon adaptation of China's apartment towers. *Building Research & Information*, *46*, 1–32.

State Council, 2012. 12th Five-Year Plan for Energy Saving and Emission Reduction in China (in Chinese). Beijing, China.

THUBERC, 2018. 2018 Annual Report on China Building Energy Efficiency (in Chinese).

Tsang, C., 2020. Energy Saving Retrofits for Residential Buildings in the Hot Summer and Cold Winter Zone in China. School of Architecture, Building and Civil Engineering.

Tsang, C., Spentzou, E., He, M., Lomas, K., 2018. Evaluating Energy Savings Retrofits for Residential Buildings in China, Presented at Building Simulation and Optimization 2018, 4th England IBPSA conference, Cambridge, UK, 11-12th Sept, pp. 284–291.

Wang, X., Lu, M., Mao, W., Ouyang, J., Zhou, B., Yang, Y., 2015. Improving benefit-cost analysis to overcome financing difficulties in promoting energy-efficient renovation of existing residential buildings in China. *Applied Energy*, *141*, 119–130.

Xu, L., Liu, J., Pei, J., Han, X., 2013. Building energy saving potential in Hot Summer and Cold Winter (HSCW) Zone , China — Influence of building energy efficiency standards and implications. *Energy Policy*, *57*, 253–262.

Yang, Q., Liu, M., Shu, C., Mmereki, D., Hossain, U., Zhan, X., 2015. Impact Analysis of Window-

Wall Ratio on Heating and Cooling Energy Consumption of Residential Buildings in Hot Summer and Cold Winter Zone in China *2015*.

Yao, J., 2012. Energy optimization of building design for different housing units in apartment buildings. *Applied Energy*, *94*, 330–337.

Yao, J., Xu, J., 2010. Effects of Different Shading Devices on Building Energy Saving in Hot Summer and Cold Winter Zone 5–8.

Yao, R., Costanzo, V., Li, X., Zhang, Q., Li, B., 2018. The effect of passive measures on thermal comfort and energy conservation. A case study of the hot summer and cold winter climate in the Yangtze River region. *Journal of Building Engineering*, *15*, 298–310.

Yoshino, H., Yoshino, Y., Zhang, Q., Mochida, A., Li, N., Li, Z., Miyasaka, H., 2006. Indoor thermal environment and energy saving for urban residential buildings in China. *Energy and Buildings*, *38*, 1308–1319.

Yu, H., Tang, B.J., Yuan, X.C., Wang, S., Wei, Y.M., 2015. How do the appliance energy standards work in China? Evidence from room air conditioners. *Energy and Buildings*, *86*, 833–840.

Yu, J., Tian, L., Yang, C., Xu, X., Wang, J., 2013. Sensitivity analysis of energy performance for high-rise residential envelope in hot summer and cold winter zone of China. *Energy and Buildings*, *64*, 264–274.

Yu, J., Tian, L., Yang, C., Xu, X., Wang, J., 2011. Optimum insulation thickness of residential roof with respect to solar-air degree-hours in hot summer and cold winter zone of china. *Energy and Buildings*, *43*, 2304–2313.

Yu, J., Yang, C., Tian, L., 2008. Low-energy envelope design of residential building in hot summer and cold winter zone in China. *Energy and Buildings*, *40*, 1536–1546.

Zhao, M., Kunzel, H.M., Antretter, F., 2015. Parameters influencing the energy performance of residential buildings in different Chinese climate zones. *Energy and Buildings*, *96*, 64–75.

Table 1: Climate characteristics (mean monthly dry-bulb temperature and relative humidity) for Chongqing

Month	Mean Dry-bulb temperature (°C)	Mean Relative humidity (%)
Jan	8.0	86
Feb	9.1	83
Mar	14.2	78
Apr	18.0	82
May	21.6	75
Jun	25.4	82
Jul	28.4	78
Aug	28.8	77
Sep	23.3	83
Oct	18.4	84
Nov	13.6	86
Dec	9.9	87

Table 2: Summary of modelling assumptions of the case study building DTM.

Building Element	Parameter	Value	Properties and reference
External wall	U-value	2.3W/m^{2}K	Three layers: 0.02m cement mortar; a 0.24m lime-sand brick; and another 0.02m lime mortar layer interior finish (Liu et al., 2015)
Roof	U-value	3.45W/m^{2}K	Five layers: 0.02m cement mortar layer, a 2mm waterproof material layer, another 0.02m cement mortar layer, and a 0.15m reinforced concrete layer with 0.01m lime mortar layer interior finish (Wang et al., 2015)
Window	U-value	5.8W/m^{2}K	3 mm single clear glazing with an aluminium frame, the percentage of window frames was 10% of the whole window (Ouyang et al., 2009; Xu et al., 2013; Yu et al., 2008)
	SHGC	0.87	
Door	U-value	2.82W/m^{2}K	Gao et al. (2014)
Partition wall	U-value	2.83W/m^{2}K	Three layers: 0.02m cement mortar, a 0.12m reinforced concrete layer, and another 0.02m cement mortar layer interior finish (Gao et al., 2014)
Internal floor	U-value	2.75W/m^{2}K	
Air infiltration rate	Air change per hour	1.5ach^{-1}	McNeil et al. (2016); Yu et al. (2008)
Overhang	Length	0m	Case study flat
COP	Heating	2.2	Yu et al. (2015)
	Cooling	2.6	
Setpoints	Heating	17.7°C	Li et al. (2018b)
	Cooling	27.9°C	Li et al. (2018b)
Heat gain	Lighting	6W/m^2	MOHURD (2013)
	Equipment	4.3W/m^2	MOHURD (2010a)
	Occupants	6.6W/m^2	ASHRAE (2018)
Ventilation rate	Summer	3.2ach^{-1} (living room), 1.9ach^{-1} (bedroom)	CIBSE (2015)

Table 3: Thermophysical properties of construction materials used in DTM models.

Material	Conductivity (W/mK)	Specific heat (J/kgK)	Density (kg/m^3)
Cement mortar	0.93	1050	1800
Lime-sand brick	1.1	1050	1900
Lime mortar	0.81	1050	1600
Reinforced concrete	1.74	920	2500
Waterproof material	0.23	1620	1050
EPS insulation	0.03	1380	30
uPVC window frames	0.17	900	1390
Aluminium window frames	160	880	2800
Low-e windowpanes (Solar transmittance = 0.6)	0.9	/	/
Clear windowpanes (Solar transmittance = 0.775)	0.9	/	/

Table 4: Selection of retrofit measures from 14 commonly used strategies using two selection criteria

Retrofit measures	Description	No occupant control	Passive measures
1	External wall insulation	Yes	Yes
2	Roof insulation	Yes	Yes
3	Double-glazed windows	Yes	Yes
4	Air infiltration control	Yes	Yes
5	Additional window overhang	Yes	Yes
6	Enclosed communal staircase	Yes	Yes
7	Energy-efficient AC	Yes	Yes
8	Deployable shading	No	Yes
9	Internal window blinds	No	Yes
10	Window curtain	No	Yes
11	Nigh time ventilation	No	Yes
12	External window shutters	No	Yes
13	Central heating system	Yes	No
14	Central cooling system (VRF)	Yes	No

Sources: Data from Li et al. (2019), Ouyang et al. (2009), Short et al. (2018), Yao et al. (2018), Yu et al. (2008).

Table 5: Summary of selected options for the retrofit measures.

Retrofit measure	Pre-retrofit	Post-retrofit measures	Reference
1.External wall insulation	U-value = 2.3W/m^{2}K	10mm EPS insulation U-value = 1.3W/m^{2}K	Ouyang et al. (2009); Wang et al. (2015)
		15mm EPS insulation U-value = 1.07W/m^{2}K	Ouyang et al. (2011)
		20mm EPS insulation U-value = 0.91W/m^{2}K	Gao et al. (2014); Zhao et al. (2015)
		25mm EPS insulation U-value = 0.79W/m^{2}K	Yu et al. (2008)
		30mm EPS insulation U-value = 0.7W/m^{2}K	Ge et al. (2018)
2.Roof insulation	U-value = 3.45W/m^{2}K	20mm EPS insulation U-value = 1.31W/m^{2}K	Wang et al. (2015)
		30mm EPS insulation U-value = 0.99W/m^{2}K	Yao and Xu (2010)
		40mm EPS insulation U-value = 0.79W/m^{2}K	Ouyang et al. (2011, 2009)
		50mm EPS insulation U-value = 0.65W/m^{2}K	Ge et al. (2018)
3.Double-glazed windows	U-value = 5.88W/m^{2}K, SHGC = 0.87	Double-glazed without solar control, aluminium frame U-value = 3.9W/m^{2}K, SHGC = 0.85	Fu et al. (2017); Yao and Xu (2010)
		Double-glazed without solar control, uPVC frame U-value = 2.8W/m^{2}K, SHGC = 0.75	Ouyang et al. (2009)
		Double-glazed with solar control, uPVC frame U-value = 2.8W/m^{2}K, SHGC = 0.54	Zhao et al. (2015)
		Double-glazed low-e, uPVC frame U-value = 1.9W/m^{2}K, SHGC = 0.54	Yang et al. (2015)
		Double-glazed argon filled low-e, uPVC frame U-value = 1.5W/m^{2}K, SHGC = 0.54	Yu et al. (2008)
4.Air infiltration control	Air infiltration rate = 1.5ach^{-1}	double-glazed windows Air infiltration rate = 1.0ach^{-1}	MOHURD (2010a)
		double-glazed windows and air-tight doors Air infiltration rate = 0.7ach^{-1}	Fu et al. (2017)
		double-glazed windows, air-tight doors, and draught stripping Air infiltration rate = 0.5ach^{-1}	Fu et al. (2017)
5.Window shading	Overhang depth = 0 m	Horizontal overhang, length= 0.3m	Yu et al. (2008)
		Horizontal overhang, length= 0.5m	Yao et al. (2018); Yu et al. (2008)
		Horizontal overhang, length= 1.0m	Yu et al. (2008)
6.Enclosed communal staircase	Staircase with outdoor conditions	Staircase with fully indoor condition with external wall and window (pre-retrofit conditions)	Ouyang et al. (2011, 2009)
		Staircase with fully indoor condition with external wall and window (post-retrofit conditions)	Ouyang et al. (2011, 2009)
7.Energy-efficient A/C	Heating COP = 2.2, Cooling COP = 2.6	Grade 3 air conditioner Heating COP = 2.7, Cooling COP = 3.2	MOHURD (2010b)
		Grade 2 air conditioner Heating COP = 2.9, Cooling COP = 3.4	MOHURD (2010b)
		Grade 1 air conditioner Heating COP = 3.1, Cooling COP = 3.6	MOHURD (2010b)

Table 6: Floor area of defined thermal zones in different occupancy flats in the case study building

Type of flat	Bedroom (m^2)	Living room (m^2)	Kitchen & toilet (m^2)	Total (m^2)
Single-bedroom (case study)	16	28	10	54
Two-bedroom	28	28	10	66
Three-bedroom	42	34	17	93

Sources: Data from Short et al. (2018), Yao (2012), Yu et al. (2008).

Table 7: Characteristics of the representative area with 321 multi-storey residential buildings.

Archetype	Floor area (m^2)	Number of buildings	Total floor area (m^2)
3F1B	1530	17	26010
5F1B	3050	12	36600
8F1B	7120	26	185120
16F1B	19200	23	441600
3F2B	1530	30	45900
5F2B	3050	20	61000
8F2B	7120	44	313280
16F2B	19200	40	768000
3F3B	1530	24	36720
5F3B	3050	16	48800
8F3B	7120	36	256320
16F3B	19200	33	633600

Table 8: Predicted pre-retrofit annual energy consumption for three types of A/C operating schedule.

A/C operating schedule	Heating (kWh/m^2)	Cooling (kWh/m^2)	Total (kWh/m^2)
Low	3.38	5.85	9.24
Medium	4.92	7.22	12.14
High	6.84	9.52	16.35

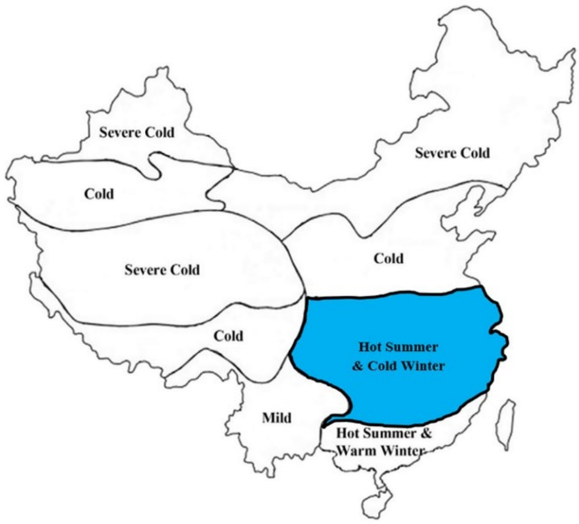

Figure 1: Five climate zones for building design in China, showing highlighted in blue the Hot Summer and Cold Winter zone (Reprinted from Building and Environment, Vol. 86, S. Gou, Z. Li, Q. Zhao,V. M. Nik, and J.-L. Scartezzini, "Climate responsive strategies of traditional dwellings located in an ancient village in hot summer and cold winter region of China," pp. 151–165, © 2015, with permission from Elsevier)

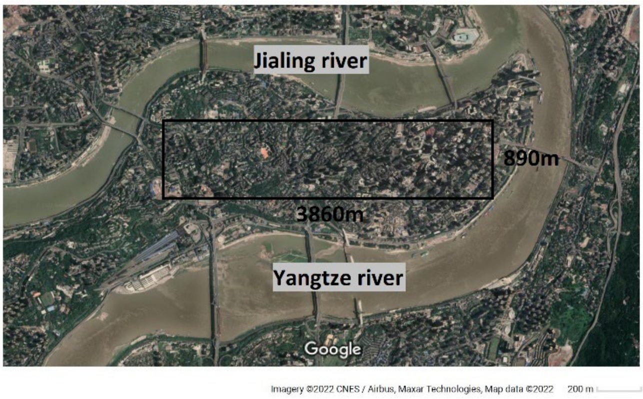

Figure 2: GoogleMap view of the Yuzhong District, Chongqing, with the selected representative area highlighted in a black box.

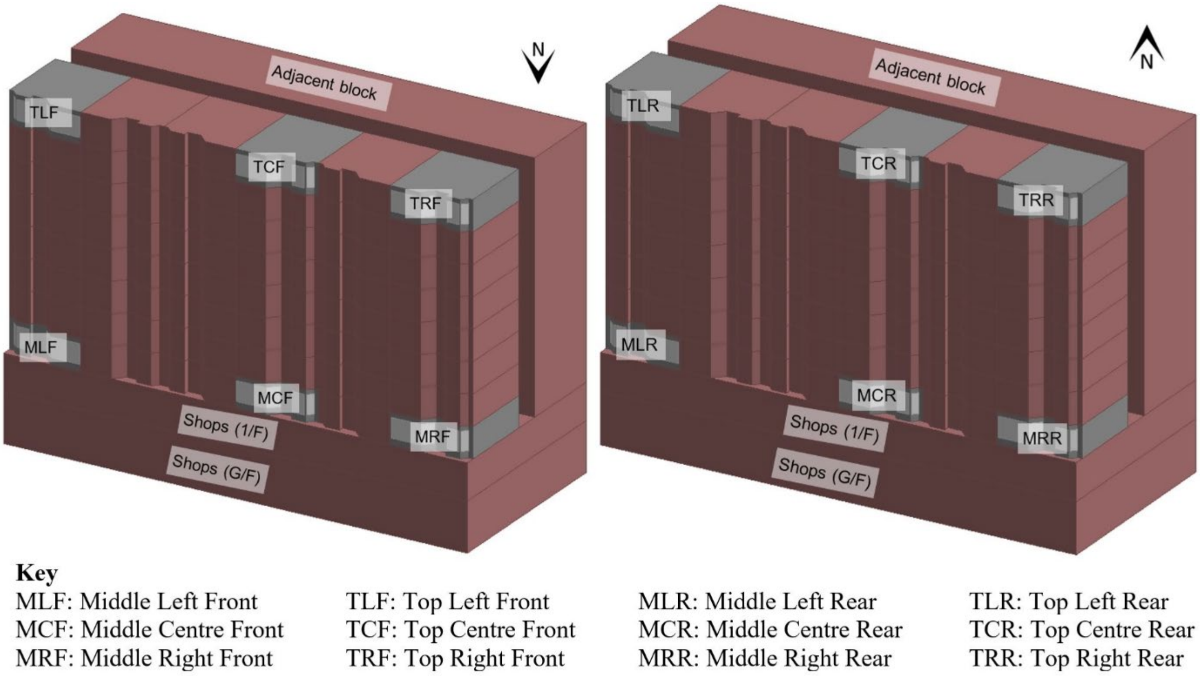

Figure 3: 3D representation of the case study building in DesignBuilder showing the location of studied flats facing front (left) and rear (right).

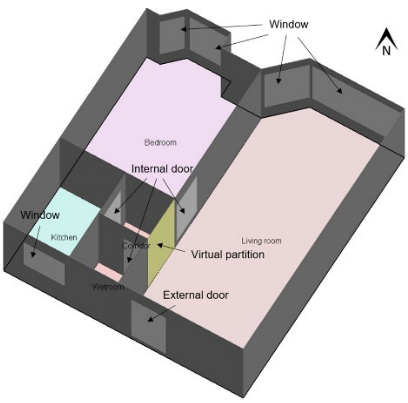

Figure 4: Axonometric view of the modelled case study flat (MCF) in DesignBuilder.

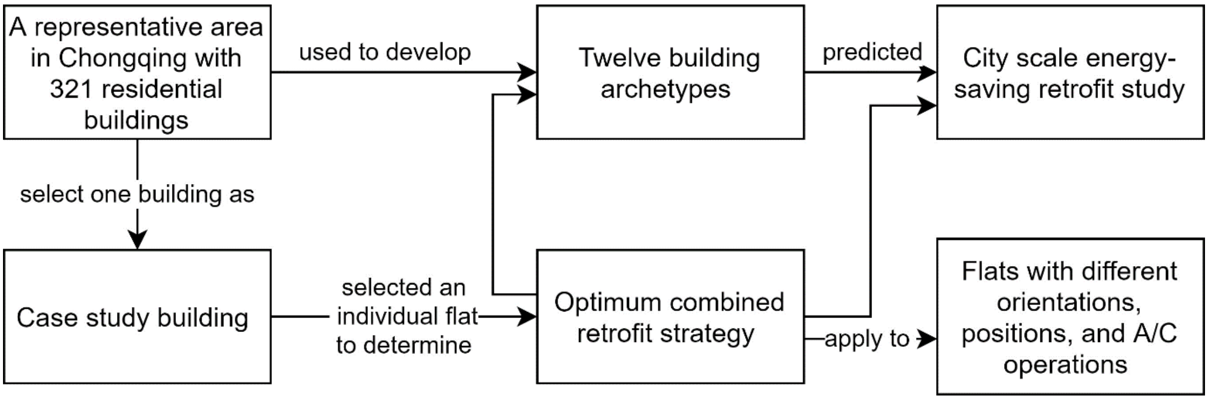

Figure 5: Summary of the dynamic thermal simulation process adopted in this study

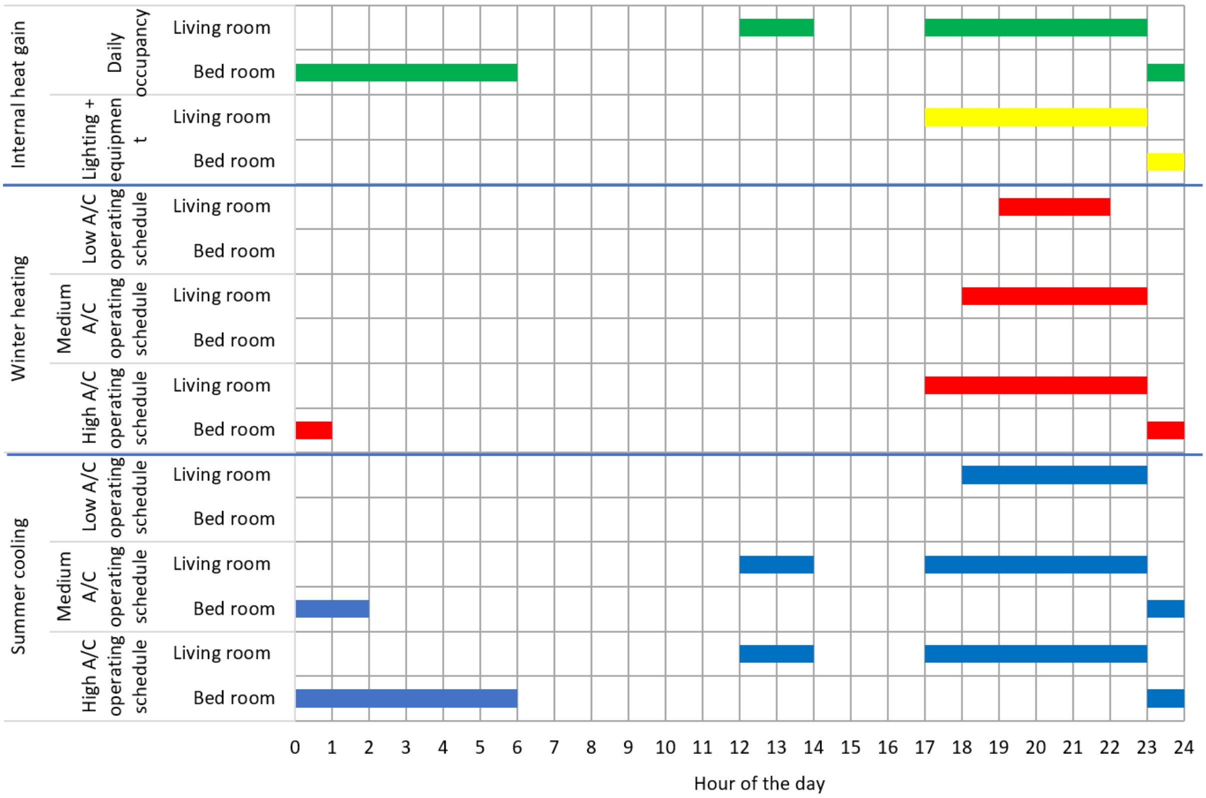

Figure 6: A/C operating schedule of cooling in summer (blue), heating in winter (red), daily occupancy (green) and lighting (yellow) for living room and bedroom.

Figure 7: View from the outdoor communal corridor and staircases of the case study building

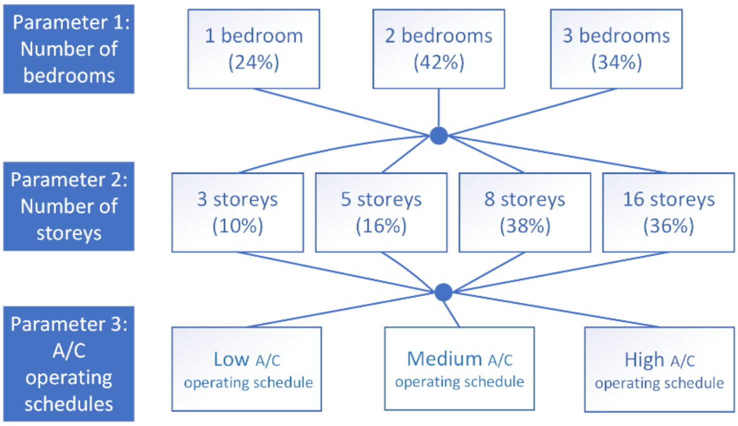

Figure 8: Parametric tree of the selected building archetypes for the development of a city-scale model.

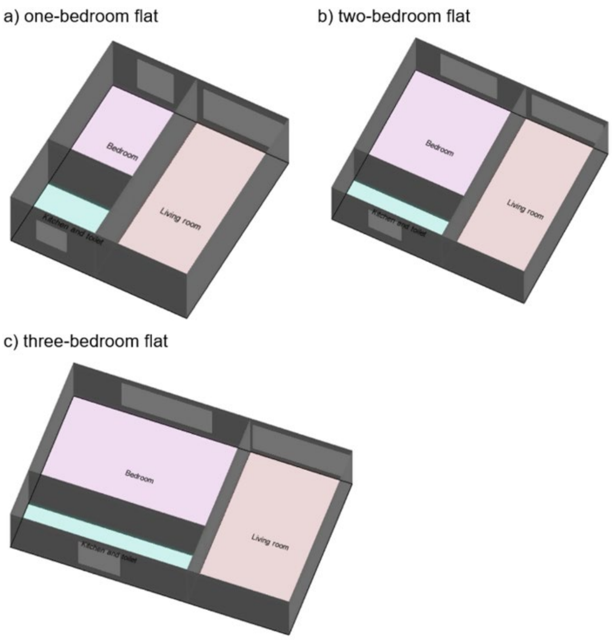

Figure 9: DTM of building archetype modelled with a) one-bedroom, b) two-bedrooms and c) three-bedrooms.

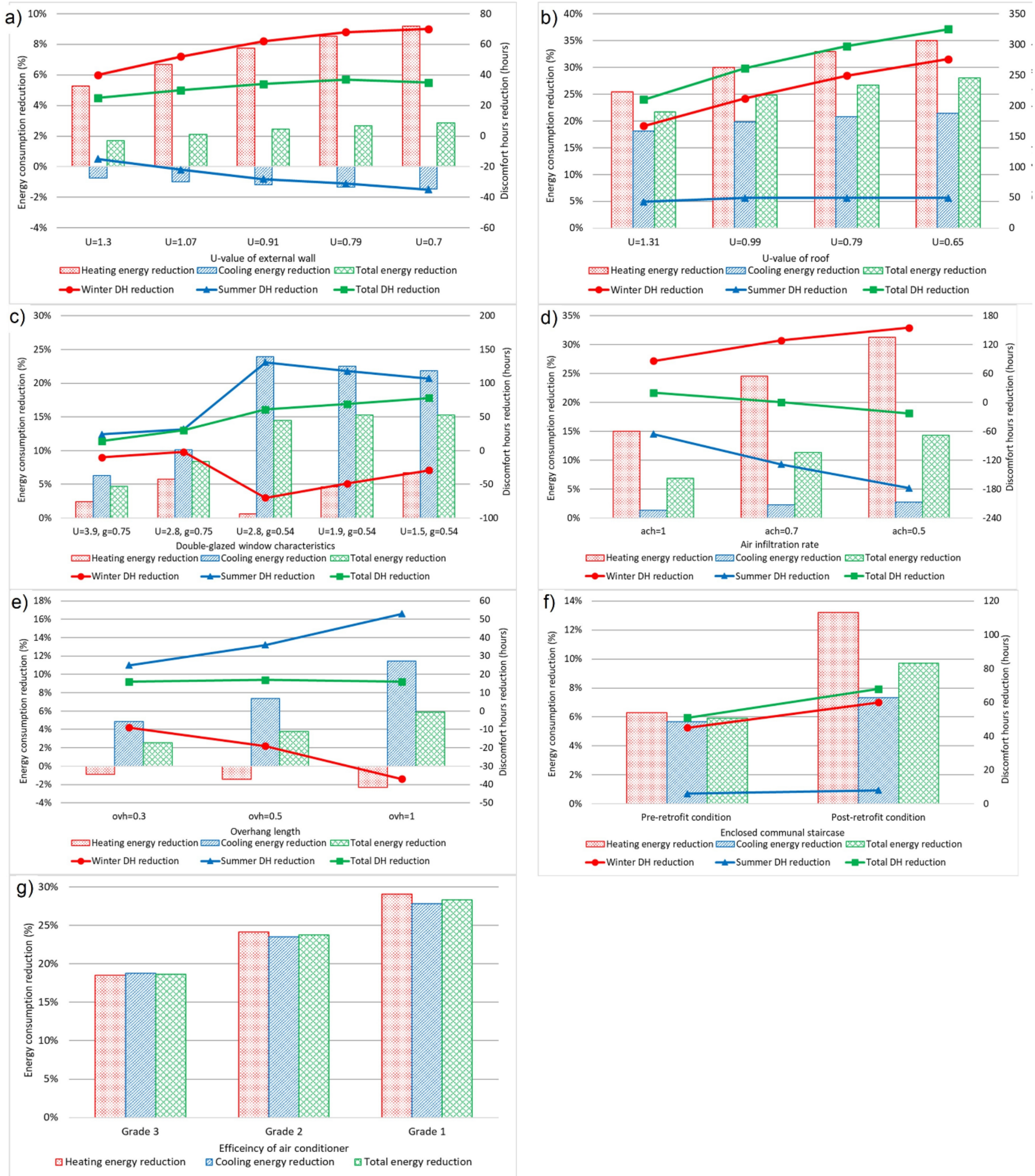

Figure 10: Energy consumption and thermal discomfort hours reduction for a) external wall insulation, b) roof insulation, c) double-glazed windows, d) air infiltration control, e) window shading, f) enclosed communal staircase, and g) energy-efficient A/C.

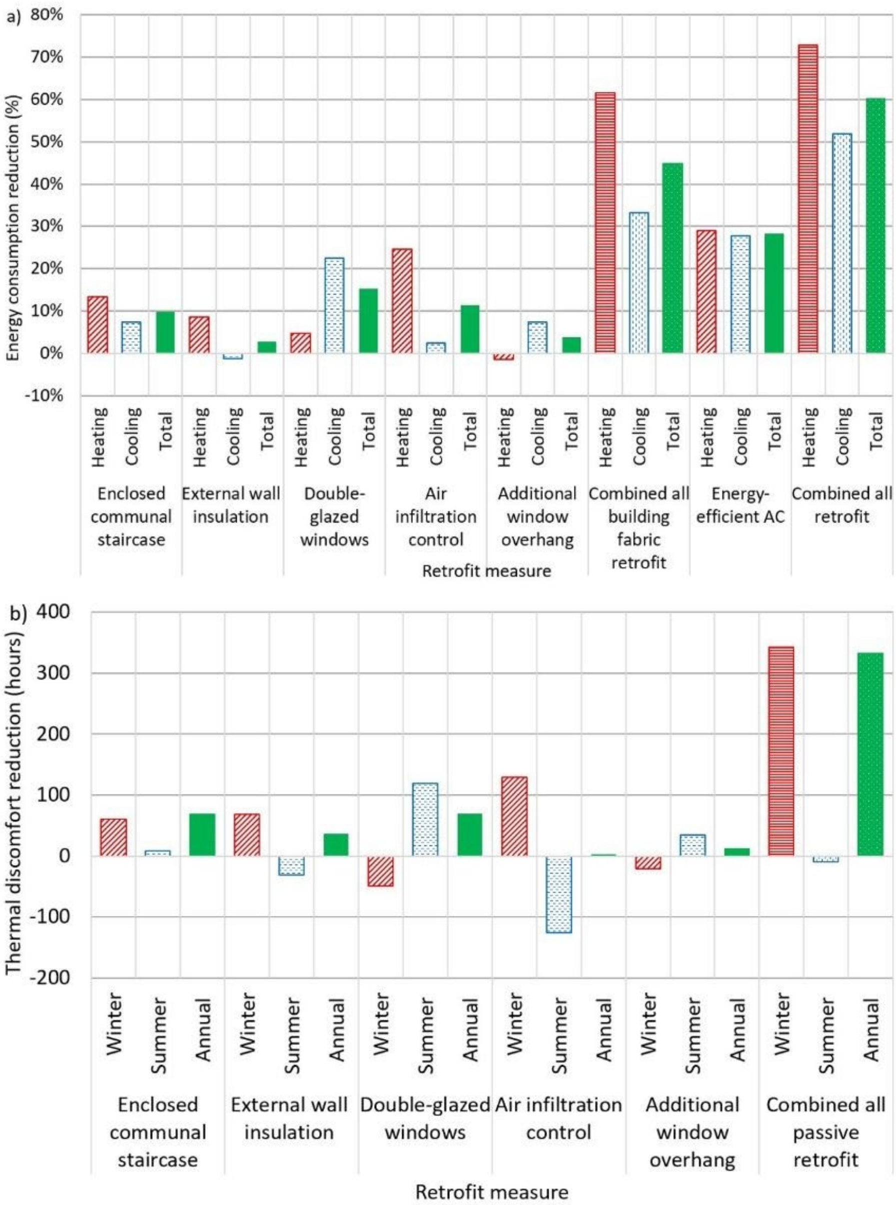

Figure 11: a) Percentage of heating, cooling and total energy reduction after optimum retrofit with the medium A/C operating strategy and b) winter, summer and annual thermal discomfort hours reduction after retrofit.

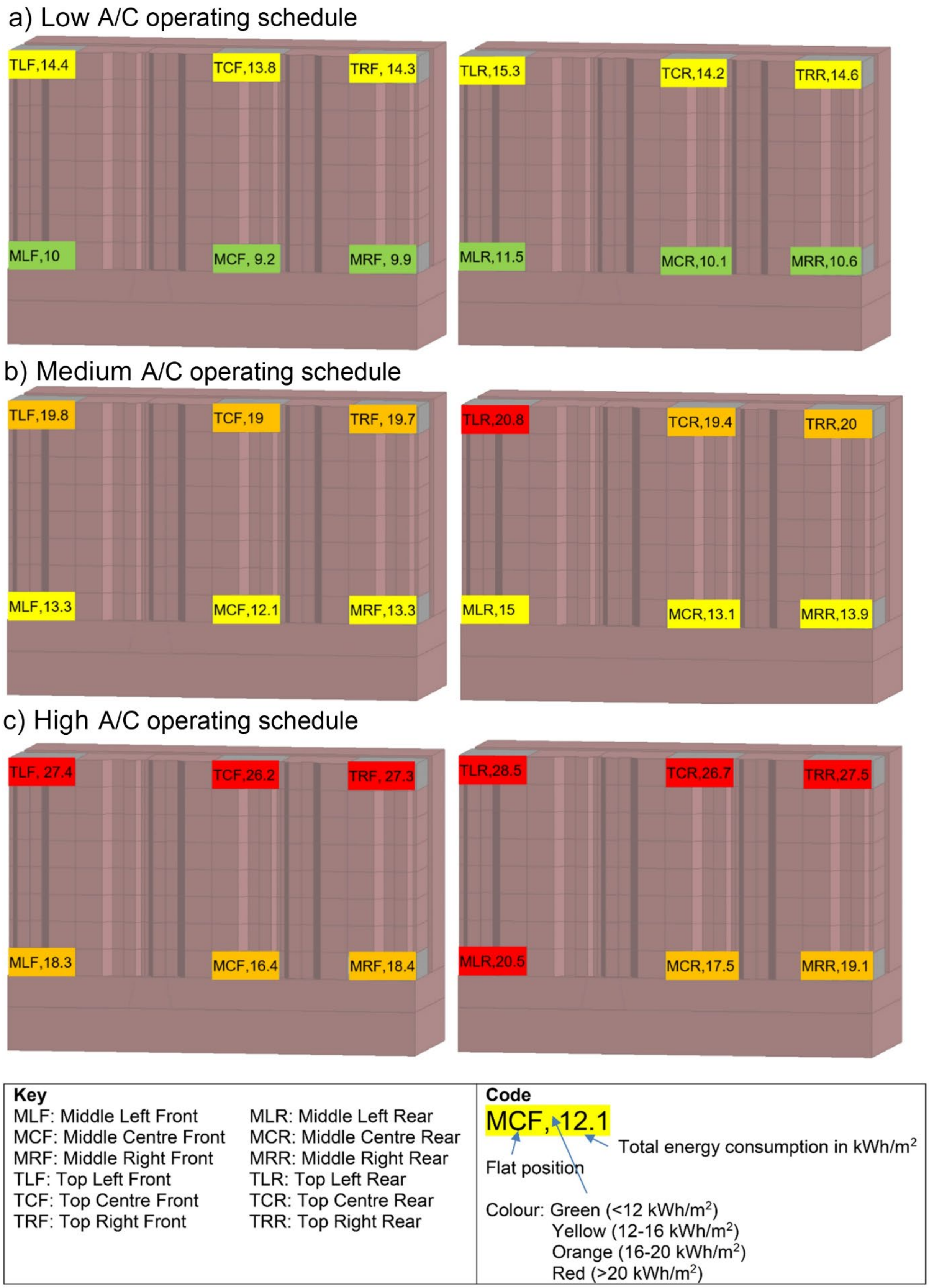

Figure 12: Predicted base-case total (heating plus cooing) energy consumption for different flats across the case study building for a) low A/C operating schedule, b) medium A/C operating schedule and c) high A/C operating schedule.

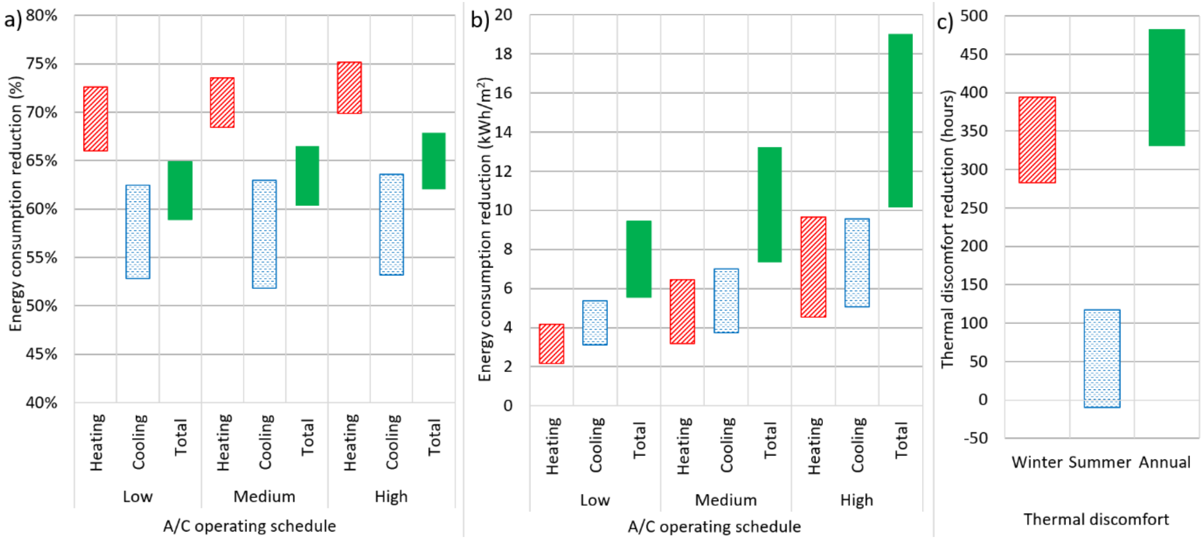

Figure 13: Impact of the optimum retrofit strategy across the different flats within the case study building: a) percentage energy reduction, b) absolute energy reduction and c) reduction in hours of thermal discomfort.

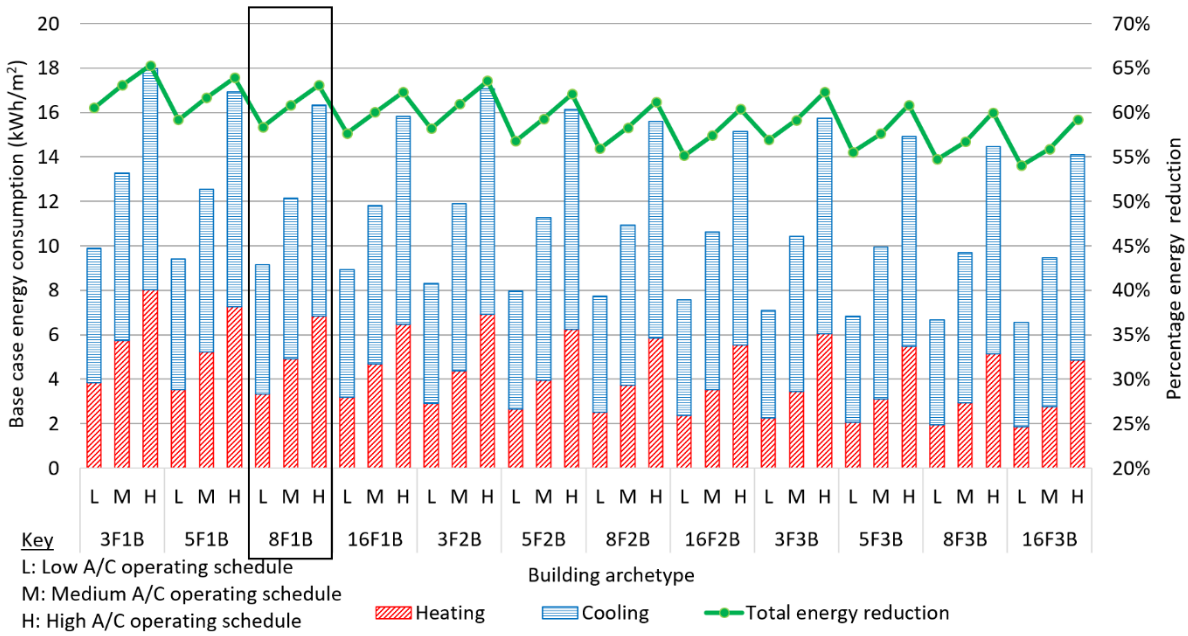

Figure 14: Predicted pre-retrofit heating and cooling energy consumption (kWh/m^2) and percentage reduction in total consumption after employing the optimum retrofit strategy for twelve building archetypes, with the case study building (8F1B) highlighted in a black box.

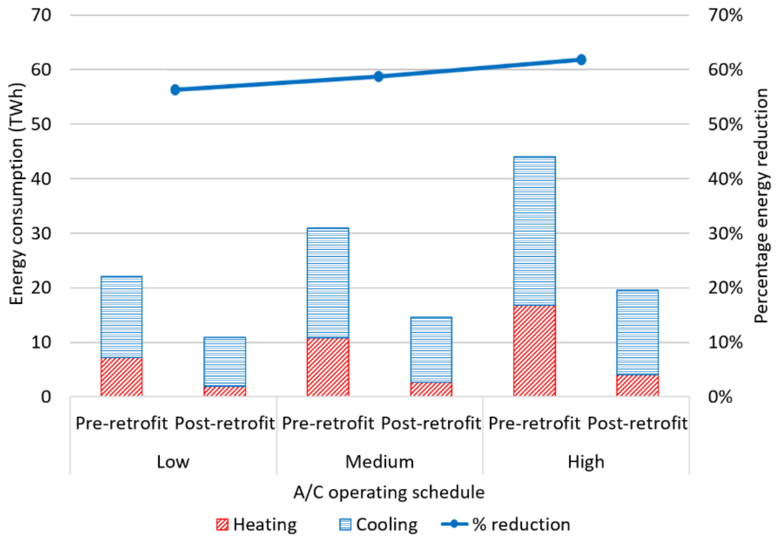

Figure 15: Predicted pre-retrofit and post-retrofit heating and cooling energy consumption (TWh) for different A/C operating schedules for the representative area with 321 multi-storey residential buildings in Chongqing, China.