Tailored Domestic Retrofit Decision Making towards Integrated Performance Targets in Tianjin, China

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ABSTRACT

Due to global warming and energy exhaustion, building retrofitting has attracted increasing attention worldwide. With 67.1 billion square meters of existing building area, China normally targets separate defect remedies to improve building energy efficiency in conventional renovation practices rather than taking a holistic approach to optimize whole building performance.

This article presents a working procedure that is employed in the decision-making process of domestic retrofits in China from an architect's perspective, combining building-sculpt redesign with the overall performance targets. This study examines three representative residences of different ages and dimensions as case studies to demonstrate a simulation-based holistic approach of integrating form, fabric and system strategies to improve environmental performance and reduce house-hold energy consumption without compromising building aesthetics in retrofit design. Different retrofit routes and corresponding priorities should be applied towards different conditions for different purposes. The

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simulation results indicate that within the service life, the older the residence, the greater the retrofit potential. For the 1981 residence, a holistic approach could achieve an energy savings of 78.1% and a CO_2 savings of 92.6%. For the 1995 case, the holistic approach could reduce energy consumption by 66.6% and CO_2 emissions by 76.6%. When designed properly, a 36.9% reduction in energy consumption and a 44.6% reduction in CO_2 emissions could be achieved for the 2002 residence.

KEYWORDS

Building stock, Domestic retrofit, Simulation, Holistic approach, CO_2 emissions, Energy savings.

1 INTRODUCTION

Facing sustained climate deterioration and the daunting prospects of resource utilization, China must explore more sustainable urban development and environmental protection. The Chinese Government announced that China will reduce the intensity of carbon dioxide emissions per unit of GDP in 2020 by 40 to 45 percent compared to 2005 levels at the 2009 Climate Change Conference in Copenhagen. Meanwhile, energy conservation and emissions reduction in the construction industry has become one of the key targets of China's 12th Five-Year Plan. At the 2014 G20 Brisbane Summit (Australia, Nov.2014), President Xi declared that China's carbon dioxide emissions will peak in 2030 [1].

A literature review revealed that the majority of previous retrofit studies have focused on two categories of research. In one type, the alternative retrofit measures are predefined according to the specific building type, dimensions, function and climatic conditions, which are then verified by simulation. In the other, a series of multi-criteria-based decision-making methods were developed to reach a final decision among implicitly defined solutions [2,3,4].

From a designer's perspective, the interrelationship between building form and climate has concerned architects and urban planners since 1960 [5], [6]. Designers devoted themselves to shaping their building following natural forces and vernacular characteristics [7], [8]. In the practice of the building industry, the critical decisions made at the early design stage often rely on the experience of the planners and designers who do not have much knowledge about the quantitative details. These uncertain variables may strongly influence the final consequences, perhaps causing the original intention to achieve unsatisfactory results [9]. There may be no assurance for the proposed plan to work effectively. Proceeding with the specific retrofit measures or not depends on the integration of a number of heterogeneous specialties, including ecological, comfort, aesthetic, financial, and so on [10]. Therefore, the development and application of tools that can assist designers in considering as many alternatives and decision criteria as possible is obviously needed.

In China, existing research shows the difficulties of renovation works in management and the unification of proprietor intentions. Energy-efficient renovation is effective for upgrading existing residential building performance but requires more government financial subsidies [11]. A real project in China tends to make separate defect remedies to improve the building energy efficiency rather than taking a holistic approach to optimize the whole building performance. Currently, many criteria have to be taken into account to provide an eco-friendly, comfortable environment with building aesthetics and low cost.

For a designer, no unique solution exists that is universally applicable to all practice. This paper emphasizes combining different retrofit methods and tools to optimize building performance at the initial design stage from an architect's perspective towards China's construction reality. In the next section, the background of Tianjin's domestic retrofit and benchmarks are illustrated. The working procedure employed to support retrofit decisions is presented with details regarding tools and parameters. Three residence case studies carried out in the proposed approach are discussed to show the simulation in practice in Section 4. The cases are then compared to illustrate the different measures for different building types in Section 5. The last section makes conclusions, and describes issues for future research.

2 BACKGROUND

2.1 Domestic retrofit in Tianjin, China

2.1.1 China's Building Stock

Buildings represent an important sector for energy consumption. Approximately 27.8% of the total national energy consumption in China is associated with energy use in buildings [12], of which 78.7% is attributed to residential buildings [13]. As early as 2005, the Ministry of Construction (MOC) published a 'Guide for Developing Energy Efficiency in Residential and Public Buildings', which explicitly set targets for building energy efficiency. New domestic buildings constructed during the '11th five year plan (2006-2010)' should consume 50% less energy compared to the baseline 1980s building; this plan also proposed a long-term objective of 65% energy savings in large cities by 2020. At the same time, retrofitting existing energy-intensive buildings was incentivized to reach 25% of total floor area in large cities before 2010; by 2020, this figure will reach 100% [14].

Among 67.1 billion square meters of existing building area, the total domestic building area is approximate 48.6 billion square meters [15,16]. Nearly 52% urban residences was constructed before 2005 without much concern for energy efficiency [17,18]. As shown in Figure 1, the solution relying purely on new building stock would fall a long way short of the target of Chinese government. The significance of improving the energy efficiency of China's existing building stock has been recognized by both the government and researchers.

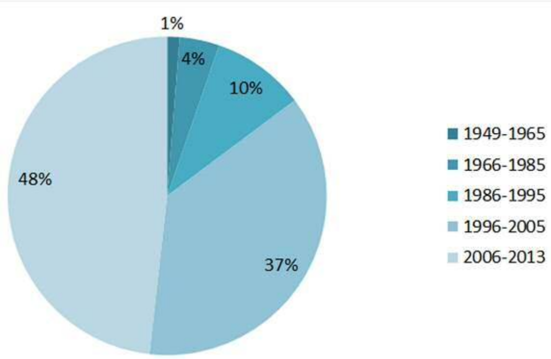


Figure 1 Age of properties in China urban
Source：THUBERC, 2015; MOHURD,2005；NBS, 1987-2001;
Note：
a. THUBERC represents Building Energy Conservation Research Center, Tsinghua University, China.
b. MOHURD denotes Ministry of Housing and Urban-Rural Development, China
c. NBS is National Bureau of Statistics,China

2.1.2 A Classification of Residential Buildings in the Cold Zone

The local climate to which the building is exposed plays a significant role in decision making about optimizing the surrounding environment and selecting climate responsive retrofit measures for the welfare of the building environment. According to the thermal zoning classification, there are five different climate divisions in China. The Cold Zone (C) is located in northern China and is in dire need of thermal insulation as well as space heating due to the cold winter weather. Therefore, this zone shows great potential for domestic energy efficiency retrofits.

However, even within the same climatic zone, buildings are exposed to different retrofit challenges due to their different characteristics as a result of the materials available and form characteristics when the building was constructed. For example, the pre-1965 residential buildings in northern China are normally low-rise slab-type apartments, with solid wall construction and courtyards. Since the 1990s, more attention has been paid to the cost intensity and land efficiency of residential buildings, and the evolution of prefabricated construction promoted the development of high-rise residential towers. Table 1 classifies the residential buildings in the Cold Zone.

Table 1 *A classification of residential buildings in the Cold Zone and their retrofit potentials*

	Property Type	External wall construction	Form characteristics	Energy efficiency design target	Conventional renovation measures
Pre - 1965	Low-rise slab-type	Clay brick wall, un-insulated	Several bed-sitting flats surrounding a courtyard	Exceeds the serve limitation of 50 years.	-
	Tube-shaped apartment	Clay brick wall, un-insulated, bamboo reinforcement,	A corridor separates rooms door to door. One room is for one family, with more than ten families on one floor.		
1966 - 1985	Mid-rise slab-type	Brick and concrete masonry structure, un-insulated	Industrialized residence. Several two-bedroom flats accessed by one staircase	Rapid growth to meet social needs	Dilapidated housing rehabilitation Passive strategy (Structural strengthening, EWI,RFI, WinR, Enclose balcony and stairway, Flat to pitched roof)
1986 - 1995	Mid-rise and small high-rise	Masonry structure or frame structure, internal wall insulation with thermal mortar	Two flats sharing one staircase with segregation of living area and common activity area	A 30% energy reduction [19]	Energy savings renovation (EWI, RFI, WinR, Flat to pitched roof, Heating system replacement, Renewable energy use)
1996 - 2005	High-rise towers	Shear wall structure, insulated with EPS/XPS	Butterfly style plan with large units Three or four rooms in a flat	A 50% energy reduction（65% in a large city） [20]	Energy savings renovation (Heating system replacement, Renewable energy use)
Post - 2005	A variety of forms with reasonable fabric constructions meeting *Guide for Developing Energy Efficiency in Residential and Public Architecture*			A 65% energy reduction	-

Note:

a. Energy efficiency design targets are compared to the 1980 baseline building

b. EWI is external wall insulation, RFI is roof insulation, and WinR is window replacement

As shown in Figure 1 and Table 1, 48% of the total domestic residential buildings were constructed after 2005 which inherently takes the 65% energy reduction target into account. Conversely, the pre-1965 properties that have already exceeded the service life (50 years) without any concern for insulation only comprise 1% of the total domestic floor area. Therefore, the domestic buildings covered in this paper focus on those with both retrofit potential and service capability, which were built in 1966-1985 (4%), 1986-1995 (10%) and 1996-2005 (37%).

With the expanding urban population and increasing housing density, domestic buildings tend to be developed as high-rise towers with big volumes, large depths and multifamily units. These characteristics result in flats with a single orientation, causing inefficient natural ventilation and unilateral lighting. Both the natural cooling effect of air movement and the health effect of sun light exposure are weakened in these flats. Thus, this article places more emphasis on the comprehensive performance optimization by integrating wind and lighting environment improvements with energy reduction in domestic retrofit design.

The municipal central systems about heating for thermal comfort, gas for cooking, water for life and sanitary sewage in Chinese city are relatively sophisticated since the 1950s. Installing centralized heating systems is a mandatory urban infrastructure updating all-pervading the north part, which is better than intermittent local heating supplies for the purpose of improving heating efficiency and reducing GHG emissions. An assumption is made in this study that all residences share the same concentrated system updated by government. Meanwhile, the energy consumption includes heating, cooling, lighting and DHW at runtime.

2.1.3 Retrofitting Practice in Tianjin

Tianjin is a representative city in the Cold Zone of north China with a total domestic building stock of 226 million m^2 [21]. Nearly half of the properties were built between 1966 and 2005 and therefore have great retrofit potential and service capability as discussed above. According to statistics, the annual energy consumption per household in Tianjin is 52.53 GJ/a, with 66.32% of the total used for space heating [22].

The large-scale retrofit practice in Tianjin started in 2006. Published in 2008, the *Technology guideline for heat metering and energy efficient residential retrofits in the northern heating region* [23] a domestic energy retrofit approach based on building envelope diagnosis and heating supply system optimization. Table 2 and Figure 2 show the frequently used retrofit design parameters in Tianjin covering building form, fabric and system optimization which will be illustrated in detail in Chapter 3. Other measures such as ground source heat pumps and smart local networks are not widely used due to the high expense and huge scale of domestic buildings. A total domestic building area of approximately 43.2 million m^2 was refurbished by 2014. *Tianjin Green Building Action Plan* promised that a residential area of 9 million square meters will be retrofitted in 2015, and another 9 million square meters will be retrofitted in 2016-2017. [24]

__Table 2__ Frequently used retrofit design parameters

	Measures		Measures
	Insulation (external wall, roof, floor, hall)		Window replacement
	Flat to pitched roof replacement		Enclosed staircase and balcony
	Green roof		Elevation greening
	Space heating(sub-metering, room temperature control)		Solar thermal Solar PV
	Shading		Energy-saving lamps
	Other tailored measures		

***Figure 2** The popular retrofit measures in Tianjin*

Source: Tianjin Bureau of Land Resources and Housing Administration,2014

2.2 Regulation and Benchmarks

There is no nationwide design regulation or evaluation standard regarding domestic retrofit in China. This article assumes that the residence should achieve the same or even better building performance after a holistic retrofit compared to the present new build. Thus, the current building regulations and energy-efficiency design standards served as the reference substratum for retrofit benchmarks.

Interaction effects exist between building groups and their surroundings. For example, the external wind environment could be influenced by the obstacles' heights and orientations and the number of indoor sunshine hours will fail to meet the basic living requirement if without considering the building interval. The reference terms set out in the related building regulations and standards are listed in Table

3.

Table 3 *Regulation and benchmarks*

	Regulation	Details
1	*Green Building Evaluation Standard GB/T 50378-2014* [25]	The surrounding external wind velocity (WV) at a height of 1.5 meters above the ground should be less than 5m/s in winter, with the wind speed amplification (WA) less than 2 to maintain a comfortable activity space.
2	*Design Code for Heating Ventilation and Air Conditioning of Civil Building GB 50736-2012* [26]	A wind speed of 0.15-0.25 m/s and an indoor air age of less than 300 s are suggested in summer without any large-area calm zone outdoors.
3	*Code of Urban Residential Areas Planning & Design GB 50183-93* [27].	The number of residential windowful sunshine hours must be more than 2 hours on the first floor on the lunar severe cold day (21 Jan or 22 Jan) for health and wellbeing
4	*Standard for Daylighting Design of Buildings GB 50033-2013* [28].	The suitable indoor daylighting coefficient should be no less than 2% in the main function rooms.
5	*Design standard for energy efficiency of residential buildings in severe cold and cold zone JGJ26-2010* [29]	All of the building envelope parameters such as wall and roof U-values should meet the stipulations in this design standard.

3 WORKING PROCEDURE

At an early design stage of building retrofit, the key problem is to quantize a range of options and identify the relatively effective measures quickly. Building simulation can serve as an effective way to predict the performance optimization related to energy reduction, carbon emissions reduction and incremental cost.

3.1 Framework and Procedure

A methodological framework based on a simulation platform has been developed to assess the energy and environment performances. The framework includes three main parts: diagnosis, proposal and prediction. An overview of the framework is illustrated in Figure 3.

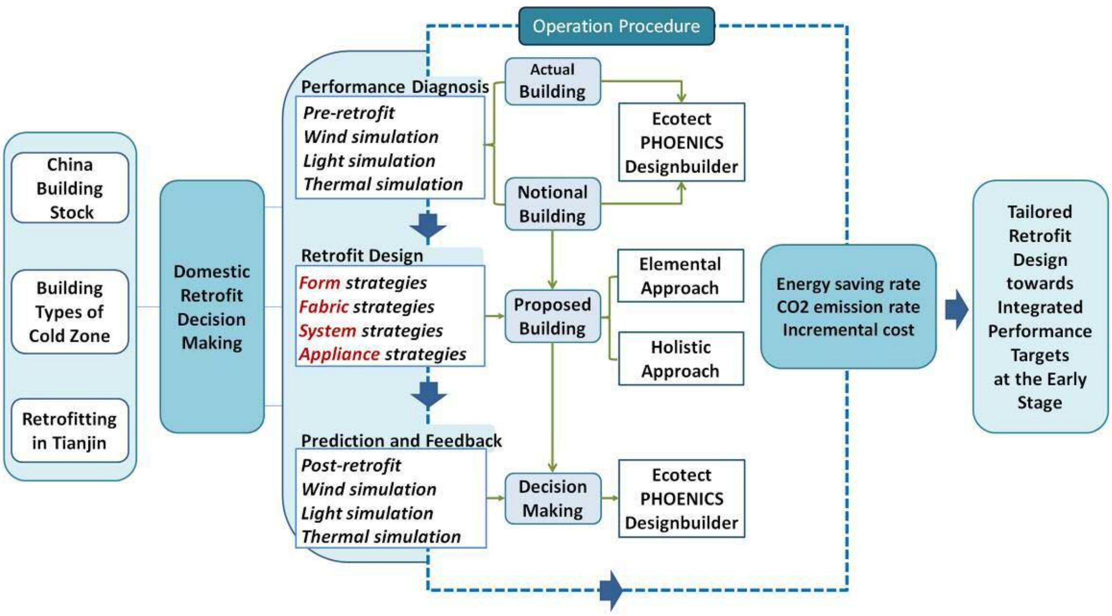


Figure 3 *Research framework*

Stage 1: Building performance diagnosis

At the assessment stage, buildings were exhaustively surveyed. Then, with the help of a simulation, the buildings performances were predicted and compared to the indicators in Chapter 2.2. The first step is a diagnosis of the physical environment with wind and lighting simulations to identify the potential occupant discomfort indoors and outdoors. Next, for thermal performance, a notional building with the same location, geometry, built environment and central system operation schedule as the actual building is built based on the latest energy efficiency design standard [30]. A comparison of the heating and cooling energy consumption between the actual building and the notional building aids decision making about which fabric parameter should be improved in the retrofit. Modelling the built environment could predict the related energy consumption, CO_2 emissions, and the performance of the physical environment and support an integrated analytical design process.

Stage 2: Retrofit proposal

In response to the defects identified by the diagnosis, both passive strategies (form and fabric promotion) and active strategies (system and appliance optimization) are proposed to improve the performance. The form strategies refer to altering the envelope and space by redesign, improving comfort and external appearance. For example, closing open stairwells can reduce heat loss, and an open-ground floor space can reduce wind velocity around the windward corners of high-rise towers. Fabric strategies reduce energy demand by updating construction, such as adding external wall insulation. Using renewable energy and altering the HVAC schedule or metering mode are system measures. The appliance approach focuses on replacing household white goods. Therefore, retrofit strategies should be tailored to match the requirements of the retrofit property with the different strategies. Table 4 summarizes the main categories of retrofit measures adopted in this research.

Table 4 *Retrofit strategies and measures*

Strategy	Objectives	Measures
Form	To improve occupant comfort by architectural redesign	Enclosed staircase , enclosed balcony, atrium , open-ground floor space, shading, pitched roof, green roof, etc.
Fabric	To reduce energy demand and improve the built environment by updating construction	Insulation(external wall, roof, floor, hall), replacing windows
System	To switch to an efficient heating and cooling schedule and to supply energy from renewable sources	Sub-metering, room temperature control Solar thermal Solar PV
Appliance	To reduce energy consumption of household appliances	Energy-saving lamps

Low carbon building design follows a route which is normally based on a fabric first sequence [31]. However, with consideration to occupant comfort of Chinese construction reality, more attention should be paid to form strategies. Besides, the financial requirements accentuated by the client and householder should not be ignored. Therefore, there will be different retrofit routes and corresponding priorities for different purposes.

Stage 3: Prediction and feedback

At the decision-making stage, each hypothetical elemental design parameter is simulated to show the benefits achieved through contrastive analysis. The building performances before and after retrofit are predicted and compared to guide the design optimization. Benefits from the retrofit strategies include operating energy savings, CO_2 emissions reduction and capital cost reduction. The best option for each residence can be identified, considering its selection foothold. Different strategies may show contradictions. For example, the form approach of adjusting light by adding reflectors may lead to more energy consumption in winter and enclosing a stairway or balcony may increase the heating and cooling areas. By comparing multifarious data, integrating elemental measures can provide a holistic approach to optimize all-round performance but with a relatively high cost.

3.2 Parametric run

Building simulation tools (BSTs) can be used within the interdisciplinary components from different physical and engineering disciplines including thermal performance, sunlight and electric lighting, fluid mechanics, and HVAC systems. Each simulation tool has a special skill for a special field rather than all-around simulation capacities for all aspects. As a result, considering the accuracy of the operation, this article uses three BSTs for different simulation. DesignBuilder v3 (DesignBuilder Software Ltd 2012), PHOENICS 2012 (CHAM 2012) and Ecotect (Autodesk 2011) were employed in this research to simulate different aspects of the retrofit optimization.

Before the simulations were started, the following information was collected:

(1) *Weather data.* Nearly every simulation tool requires the input of a local meteorological file, which can be downloaded from the EnergyPlus official site in an EPW format. The original files used in this research were produced by Tsinghua University (THU) and China Meteorological Administration (CMA). The environmental conditions for natural ventilation in this research referred to the statistics from the *Data set for building thermal environment analysis in China*; the dominant south wind in summer is 1.7 m/s with an outdoor design temperature of 29.9 °C, and the dominant north-north-west wind in winter is 5.6 m/s with an outdoor design temperature of -6.5 °C [32].

(2) *Building model.* A building model in Designbuilder has two parts; the dimensions of the house and the building fabric including materials, position and area, which are gathered from field surveys and working drawings. For PHOENICS, CFD simulations can be run in a FLAIR module with models converted from SketchUp as an available 3ds format, incorporating the setup of local wind speeds, wind directions, temperatures and other parameters including the power law index. The lighting analysis performed by Ecotect requires the input of information such as the window areas and location, the cleanliness of the windows and the sky-light conditions.

For each specific property, the actual building models were built based on information about local weather data, the surroundings, geometries, fabric and system conditions, etc. The more detailed the models are, the more accurate and realistic the output will be. The notional buildings share the same parameters as the actual building but were adjusted to meet the requirements for building component U-value, shape coefficients and window to wall ratios based on the latest energy efficiency design standard, to achieve the minimum standards for energy saving targets. The proposed buildings were a design proposal for a retrofit solution.

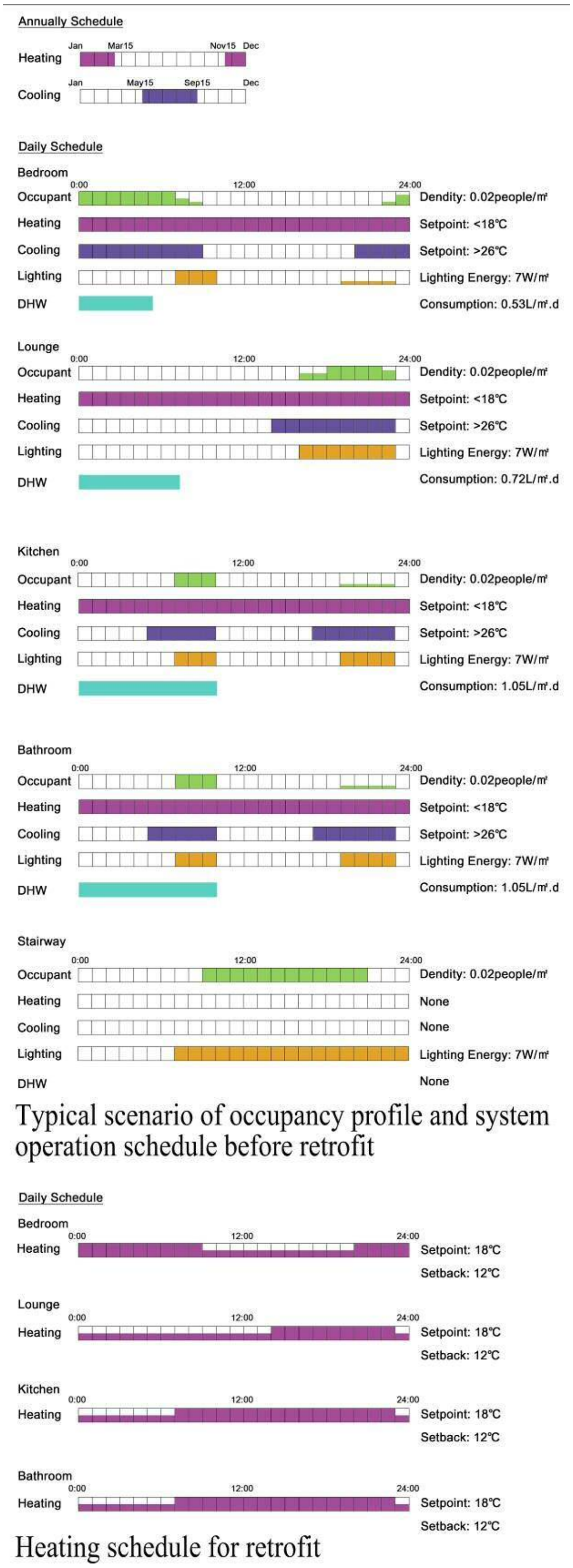


Figure 4 *System schedule comparison*

(3) *System design parameters.* Data regarding building services includes those associated with heating, cooling, lighting, and domestic hot water (DHW). The system schedule before retrofit refers to the typical scenarios

shown in Figure 4 [33]. In addition, heating was switched on or off by sub-metering and room-metering temperature control system) for different spaces to avoid unnecessary energy consumption in non-occupied periods.

⑷ *Carbon dioxide emission factor and calculation formula*. The calculation of greenhouse gas emissions refers to the definition and formula of the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* [34]. The calculation method combines the extent of human activity (called activity data or AD) with the related coefficients that quantify the emissions or removals per unit of activity (called emission factors or EF). The equation is as follows:

$$\mathbf{Emissions = AD \times EF} \qquad (1)$$

At the energy sector, fuel consumption is a direct result of human activities, and carbon dioxide emitted per unit of fuel consumed would be an emission factor.

The annual carbon dioxide emissions (E_a) from building operation are the sum of the carbon dioxide emissions produced by different fuel consumptions. For example, in the equation below, $\mathbf{E_{grid,a}}$ refers to the carbon dioxide emissions due to electricity consumption, n represents the number of other fuel types and $\mathbf{E_{fuel,ak}}$ represents the carbon dioxide emissions from the consumption of other types of fuels [35].

$$\mathbf{E_a = E_{grid,\,a} + \sum_{k=1}^{n} E_{fuel,\,ak}} \qquad (2)$$

In the Cold Zone of China, the main domestic fuels are electricity and gas. Table 5 lists the latest carbon emission factors and prices available, which are used in the calculation of carbon emissions and primary energy ratio in this research.

Table 5 Carbon emission factors and fuel prices

Fuel	Carbon emission factor	Primary energy ratio	Fuel price
Gas	2.1622 Kg CO_2/ m^3 [36]	1.33 Kgce/m^3 [37]	3.07¥/ m^3 [38]
Electricity	1.058 Kg CO_2/ KWh [39]	0.325 Kgce/KWh [40]	0.49¥/ KWh [41]

3.3 Incremental cost

The incremental cost discussed in this article is the static cost arising from the implementation of the retrofit strategies. The total cost is therefore a sum of expenses for removing useless components, buying and installing new materials or equipment, while excluding the costs for maintenance and replacements, which could be obtained from a Life cycle analysis and the consideration of inflation when more information is available. Hence, the Incremental cost of the actual building is zero, and, the total retrofit cost (ReCost) is calculated by adding together the costs of all of the retrofit measures:

$$\mathbf{ReCost=\sum_{k=1}^{n} ReCost_k} \tag{3}$$

$$\mathbf{ReCost_k= (C_K+ C_{K\text{-}DEM}) \times A_K} \tag{4}$$

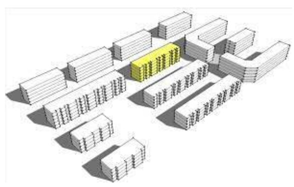
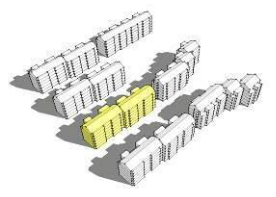
$$\mathbf{Cost\ capability=1-(ReCost_k/ReCost)} \tag{5}$$

where n represents the number of retrofit actions, A_K is the area (or amount) to be retrofitted with individual measures; C_K denotes the unit cost of individual retrofit measures; and $C_{K\text{-}DEM}$ is the cost of previous construction or equipment demolition if any exists.

4 CASE STUDIES

The three residences that were modelled include a 1981 mid-rise building, a 1995 mid-rise building and a 2002 high-rise building. They share the same geographic location, weather data and system schedules but have different dimensions, fabrics and surroundings. Similar design procedures were followed to identify efficient retrofit options for the different buildings. Table 6 summarizes their basic information before retrofit.

Table 6 *A summary of the basic building information before retrofit*

	1981Case	***1995 Case***	***2002 Case***
Community			
Plan			
Location	Tianjin, China	Tianjin, China	Tianjin, China
Weather data	Tianjin. CSWD	Tianjin. CSWD	Tianjin. CSWD
Wind environment		Summer 1.7 m/s Winter 5.6 m/s	SOUTH N-N-W
Built age	1966-1985	1986-1995	1996-2005
Project stage	Occupied	Occupied	Occupied
Floor area (m2)	2711.75 m2	4333.93 m2	17146.07 m2
Energy target	Tianjin energy efficiency design standard for residential buildings (2013)	Tianjin energy efficiency design standard for residential buildings (2013)	Tianjin energy efficiency design standard for residential buildings (2013)
Property type	Mid-rise	Mid-rise	High-rise
External wall	Solid Clay Brick wall, Un-insulated	Solid Clay Brick, 360 mm, Insulation mortar, 30 mm	Concrete, Reinforced, 200 mm, EPS Expanded Polystyrene 50 mm
Fuel	Natural gas and electric from grid	Natural gas and electric from grid	Natural gas and electric from grid
System	**Space heating**	Central heating, Hot water radiator heating, CoP=0.89	Central heating, Hot water radiator heating, CoP=0.89
System	**Space cooling**	Split cooling air conditioner , CoP=3.20	Split cooling air conditioner , CoP=3.20
System	**Domestic hot water**	Household water heater, CoP=0.85	Household water heater, CoP=0.85
Appliance	**Electric lighting**	T2 fluorescent lamp	T2 fluorescent lamp
Others	Open-styled staircase Open-styled balcony	Rooftop terrace	Bay window

4.1 CASE 1: 1981 Sijicun residence

Sijicun residential community was built in 1981 with 5-storey domestic buildings that have flat roofs. As typical 1966-1985 buildings, each floor was arranged with a stairway in the middle, surrounded by three small flats, leading to poor natural ventilation. The un-insulated brick-concrete structures and open balconies also greatly increased building heat loss. In addition, a flat was normally designed with a passage hall in the middle rather than a living room. The building marked in yellow was modelled in the study, and the building details could are shown in Table 6.

4.1.1 Diagnosis

The physical environment diagnosis showed in Figure 5 is composed of sun light hour analysis, indoor daylight factors, community wind velocity (WV) in summer and winter, and indoor wind velocity and air-age in summer. The simulation results indicate that due to relatively low building density and volume fraction, both 2 hours benchmarks of windowful daylight and comfortable air flow conditions outdoors were achieved. The summer wind velocity of most internal space is less than 0.04 m/s, which is too small to process natural ventilation. Meanwhile, the small depth causes a high daylight factor especially near the windows. Hence, the main challenge for retrofitting the physical environment is improving the indoor natural ventilation and reducing glare near the window.

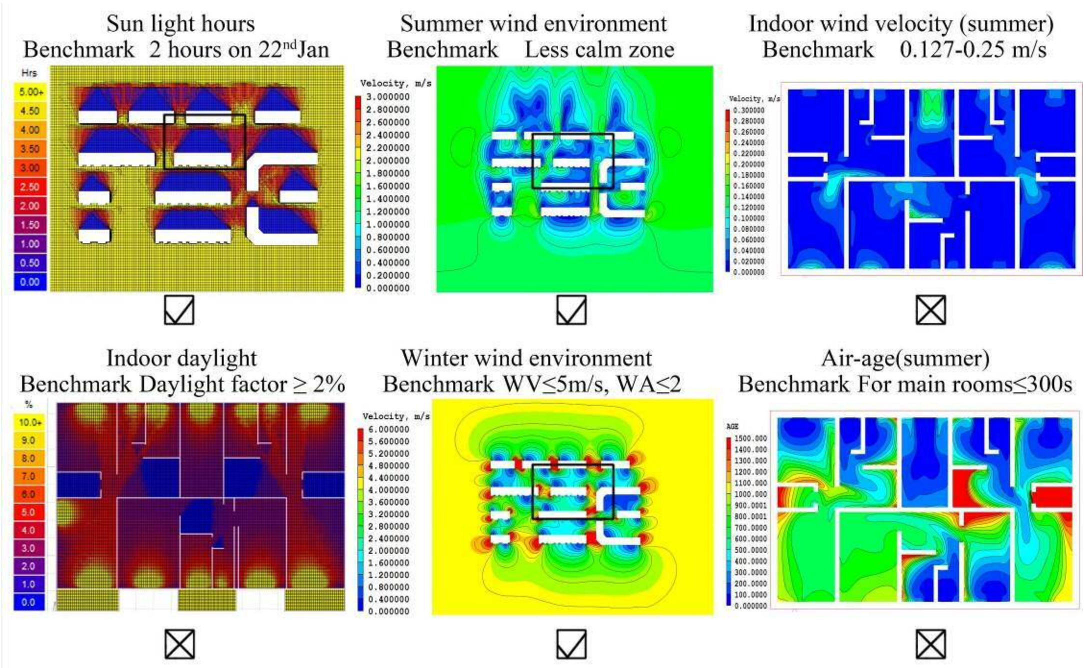


Figure 5 *Physical environment diagnosis of case 1*

Table 7 shows the fabric and system parameters of the building. The notional building established according to the *Tianjin energy efficiency design standard for residential building 2013* [42] is taken as a target reference model. Compared to the notional building, the actual building shows great potential for improving the insulation performance of the building envelope. In addition to adjusting the system metering mode, renewable energy supply was also considered. According to the simulation results, the predicted building energy consumption is almost twice that of the notional building.

Table *7 Thermal performance diagnosis for case 1*

		Actual Building		**Notional building**	**Attained**
Fabric	**Shape Coefficient**	0.39		0.33	☒
	External wall construction	Solid Clay Brick, 360 mm, U-value=**1.565** W/ m^2.k		Solid Clay Brick, 360 mm, EPS Expanded polystyrene, 65 mm, U-value=**0.439** W/ m^2.k	☒
	Flat roof construction	Concrete, Reinforced, 120 mm, Fly ash ceramics, 30 mm, U-value=**2.634** W/ m^2.k		Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 120 mm, U-value=**0.265** W/ m^2.k	☒
	Window	Single clear (6 mm) windows, U-value=**5.840** W/ m^2.k		Double-glazed low-E clear windows (3/13 mm), U-value=**1.786** W/ m^2.k	☒
	Window to wall ratio	S	0.34	0.34（0.3–0.7）	☑
		N	0.27	0.27（≤0.4）	☑
		E	0.06	0.06（≤0.45）	☑
		W	0.06	0.06（≤0.45）	☑
Energy consumption (kWh/ m^2.yr)		139.12		68.45	☒

4.1.2 Predictive Design

Following the preliminary physical and thermal simulations, 10 different measures were tailored to the requirements of the building, including enclosed balconies and enclosed staircases with an atrium, wall and roof insulation, window replacement, window shading, flat to pitched roof conversion, space heating sub-metering, solar thermal, solar PV, etc. CFD and lighting simulations were run to give specific guidance for decision making related to form retrofit. Figure 6 illustrates benefits from optimizing internal ventilation and indoor lighting. The enclosed staircase with an atrium can serve as a chimney to promote natural ventilation. According to the prediction, the sloped shading element could effectively block strong sunshine and reduce glare in summer without compromising daylight in winter.

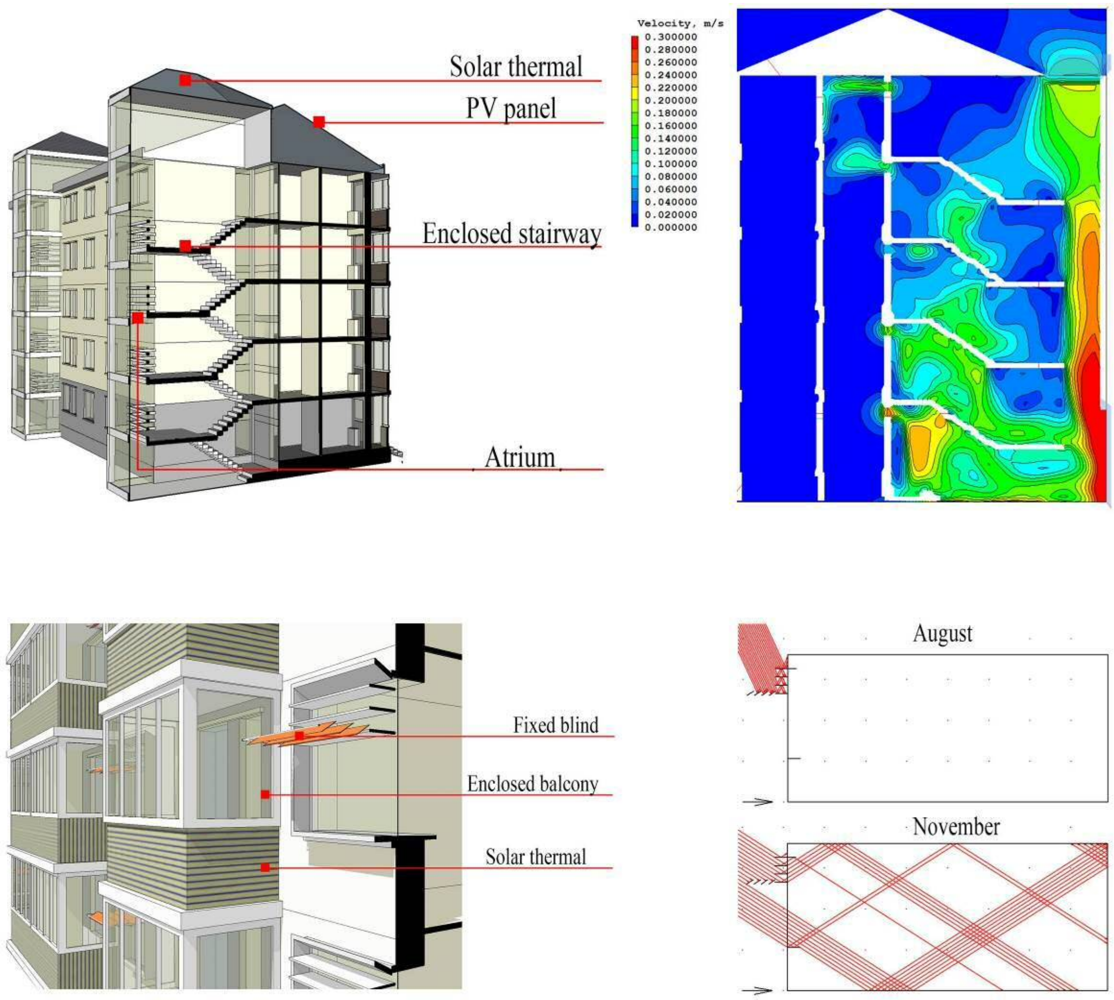


Figure 6 *Visible measures on building's appearance after redesign*

For the fabric retrofit, a layer of 65 mm EPS insulation was added to the external wall, and the existing flat roof was converted to a pitched roof insulated with 120 mm XPS extruded polystyrene. The simulation results show that EWI could contribute to a 22.7% energy savings and an 11.7% carbon emissions reduction. In addition, adjusting the heat metering mode is an effective system retrofit approach. Before the retrofit, the heating was switched on or off for the whole building without treating the rooms with and without occupants differently. By changing the operating schedule from a 24 hour whole flat heating mode to an intermittent heating one adjusted to room occupancy as mentioned in Figure 4, it could achieve an energy savings of 9.5%.

Table 8 summarizes the prediction results of energy savings, CO_2 emissions savings, incremental cost for individual retrofit strategies, and a holistic approach combining all of the measures together. In this case, the most energy efficient measure is EWI, which also has a low incremental cost. Installing solar PV is the most low carbon strategy that could reduce 20 kg of carbon emissions per square meter per year. Window shading would increase energy consumption but is good for daylight. Furthermore, enclosed balconies would result in negative energy savings rather than positive savings due to the increased heating area. The proposed holistic approach could achieve an energy saving of 78.1% and a CO_2 emissions reduction rate of 92.6% with an increment cost of 96.36 pounds per square meter.

Table 8 *Performance optimization prediction for the 1981 Sijicun residence in relation to the retrofit measures*

		Measures	Details	Energy Consumption (kWh/㎡·yr)	Average savings (%)	CO_2 (kg/㎡·yr)	CO_2 savings (%)	Incremental cost (£/㎡)
Before retrofit								
Actual building		**-**	**-**	**139.12**	**-**	**52.90**	**-**	**-**
After retrofit								
Elemental Design Parameter	**Form Strategy**	Enclosed staircase with atrium	Reduce shape coefficient, create a chimney effect, develop public communication space.	121.17	12.9	48.12	9.0	9.33
		Enclosed balcony	Increase floor area	137.46	1.2	52.34	1.0	7.67
		Shading	Window shading on south facade	139.89	-	52.68	0.4	0.96
		Flat to pitched roof conversion	Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 120 mm, U-value=0.265 W/ m^2.k	121.05	13.0	49.05	7.3	14.40
	Fabric Strategy	External wall Insulation	Solid Clay Brick, 360 mm, EPS Expanded polystyrene, 65 mm, U-value=0.439 W/ m^2.k	107.50	22.7	46.70	11.7	5.81
		Window	Double-glazed low-E clear windows (3/13 mm), U-value=1.786 W/ m^2.k	124.63	10.4	49.52	6.4	8.67
	System Strategy	Space heating	Sub-metering and room-metering temperature control	125.95	9.5	50.26	5.0	12.62
		Solar thermal	Domestic hot water heating, 135.81 m^2 solar thermal collector installed on the balconies	125.65	9.7	38.65	26.9	13.08
		Solar PV	Solar electrical energy generation, 47.17 kW Photovoltaic panels installed on the roof	120.22	13.6	32.90	37.8	20.87
	Appliance Strategy	Electric lighting	LED lighting	135.62	2.5	47.80	9.6	2.94
Holistic approach				**30.51**	**78.1**	**3.93**	**92.6**	96.35

4.2 CASE 2: 1995 Jiuhuali residence

The second case study was chosen to represent the 1986-1995 building that is typical of 6-storey high buildings with internal insulation coating. The Jiuhuali community was an ideal case of low density building groups with segregation of the living area and the common activity area. Each unit was designed with two flats per floor sharing one staircase, enabling sufficient daylighting and natural ventilation.

4.2.1 Diagnosis

Following a procedure similar to that described above, the Jiuhuali residence shows its distinction. Figure 7 illustrates that the sun light hours for buildings in the north fails to meet the 2 hours requirement because the building intervals are too close. Furthermore, although most of the main living spaces meet the daylight factor requirement, the glare level near the window is still outside of the

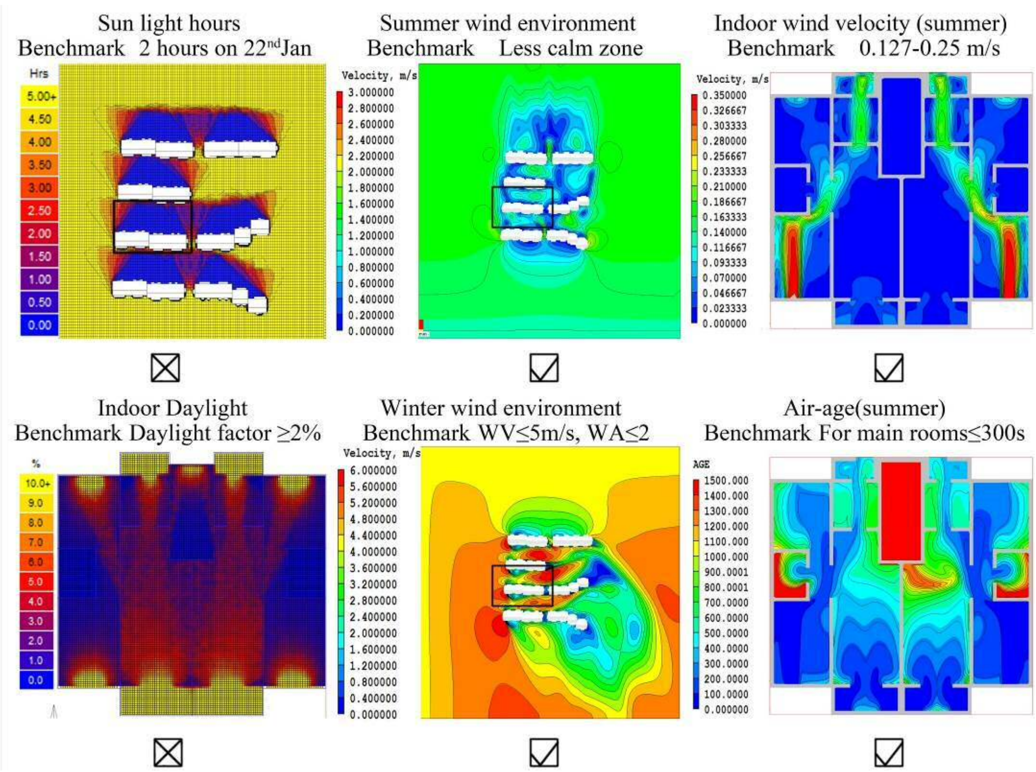


***Figure** 7 Physical environment diagnosis of case 2* comfort zone.

A number of design measures could improve the thermal performance and system management. All of the parameters that are inferior to those of the notional building would be optimized in the retrofit design. Table 9 shows that the energy consumption before retrofit is 107.49 kWh/ m^2.yr with the target after retrofitting of 68.18 kWh/ m^2.yr.

Table 9 *Thermal performance diagnosis for case 2*

		Actual Building		**Notional building**	**Attained**
Fabric	**Shape Coefficient**	0.29		0.29	☑
	External wall construction	Solid Clay Brick, 360 mm, Insulation mortar, 30 mm, U-value=**1.295** W/ m^2.k		Solid Clay Brick, 360 mm, EPS Expanded polystyrene, 60 mm, Insulation mortar, 30 mm, U-value=**0.442** W/ m^2.k	☒
	Roof construction	Concrete, Reinforced, 120 mm, Polystyrene foam board, 50 mm, U-value=**0.661** W/ m^2.k		Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 120 mm, Eco roof material, 60 mm, U-value=**0.248** W/ m^2.k	☒
	Window	Single clear (6 mm) windows, U-value=**5.778** W/ m^2.k		Double-glazed low-E clear windows (3/13 mm), U-value=**1.786** W/ m^2.k	☒
	Window to wall ratio	S	0.33	0.33（0.3–0.7）	☑
		N	0.24	0.24（≤0.4）	☑
		E	0.13	0.13（≤0.45）	☑
		W	0.08	0.08（≤0.45）	☑
Energy consumption (kWh/ m^2.yr)		107.49		68.18	☒

4.2.2 Predictive Design

After modification and prediction, the “extrude object for solar envelope” analysis helped to locate which part of the building should be cut down to reduce the adverse effects to its neighbours without affecting the building’s normal use (Figure 8).

As shown in Table 10, 10 measures examined were examined in case 2 involving form strategies (volume control, elevation greening, and shading), fabric strategy (EWI, green roof, window update), system optimization (space heating schedule, solar PV and solar thermal), and electric lighting replacement. According to the simulation results, window updating is the most effective measure with an energy saving rate of 19.5%, while solar thermal could reduce CO_2 by 25.6%, making it the most low carbon measure. LED lighting is the most cost effective option with a CO_2 reduction rate of 13.1%. The holistic approach of combining all of the strategies together can reduce energy consumption by 66.6% and CO_2 emissions by 76.6%.

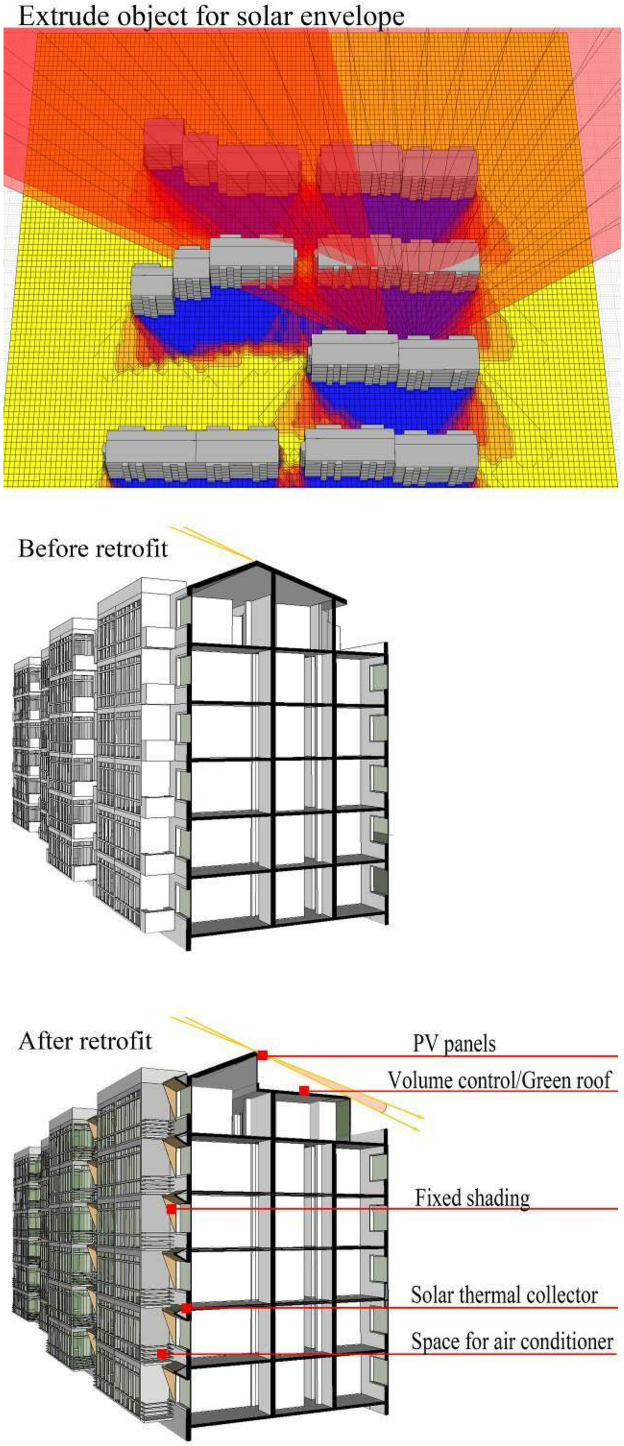


Figure 8 *Visible measures on building's appearance*

Table 10 *Performance optimization prediction for the 1995 Jiuhuali residence in relation to the retrofit strategies*

		Measures	Details	Energy Consumption (kWh/㎡·yr)	Average savings (%)	CO_2 (kg/㎡·yr)	CO_2 savings (%)	Incremental cost (£/㎡)
Before retrofit								
Actual building		-	-	**107.49**	-	**51.55**	-	-
After retrofit								
Elemental Design Parameter	**Form Strategy**	Volume control	Cut the roof according to the sun envelope	106.51	0.9	51.14	0.8	4.57
		Elevation greening	Vertical green on east and west facade	105.81	1.6	51.11	0.9	0.61
		Shading	Window shading on south facade	108.16	-0.6	51.47	0.1	0.72
	Fabric Strategy	External wall insulation	Solid Clay Brick, 360 mm, EPS Expanded polystyrene, 60 mm, U-value=0.442 W/ m^2.k	93.73	12.8	49.14	4.7	5.26
		Green roof	Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 120 mm, Eco roof material, 60 mm, U-value=0.248 W/ m^2.k	104.81	2.5	51.01	1.1	5.99
		Window	Double-glazed low-E clear windows (3/13 mm), U-value=1.786 W/ m^2.k	86.54	19.5	46.37	10.0	17.97
	System Strategy	Space heating	Sub-metering and room-metering temperature control	95.72	11.0	49.20	4.6	8.43
		Solar thermal	Domestic hot water heating, 180.63 m^2 solar thermal installed on the balconies	95.01	11.6	38.35	25.6	8.73
		Solar PV	Solar electrical energy generation, 42.86 kW photovoltaic panels installed on the roof	98.27	8.6	41.79	18.9	11.86
	Appliance Strategy	Electric lighting	LED lighting	102.61	4.5	44.77	13.1	1.96
Holistic approach				**35.85**	66.6	**12.04**	76.6	66.1

4.3 CASE 3: 2002 Xinyuancun residence

Xinyuancun residential district was built in 2002 to provide housing for faculty of Tianjin University. This district includes six 29-storey high-rise buildings and one medium high-rise building with accessory public facilities. As a typical 1996-2005 high-rise building group (Figure 11), the building facades were decorated with bay windows. Most of the flats have a small width and large depth layout, resulting in relatively poor lighting and ventilation performances of the flats in the middle. A standard floor in one of the buildings was selected for the study.

4.3.1 Diagnosis

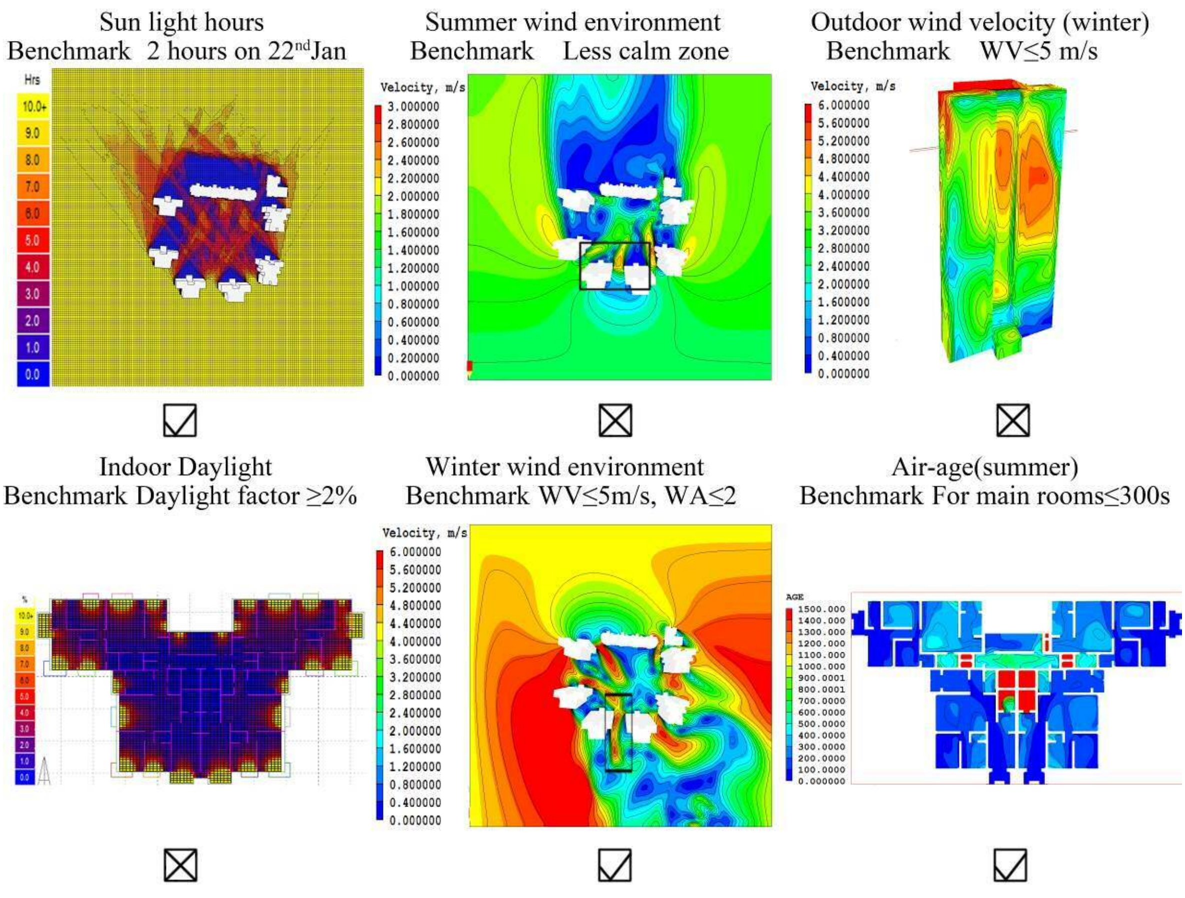


***Figure 9** Physical environment diagnosis of case 3*

The high-rise building built in 2002 was relatively new among the three cases. According to the physical environment diagnosis shown in Figure 9, the wind velocities around the windward corner of the buildings increase greatly, especially on the ground level and top level (nearly 5 m/s). Meanwhile, the deep-plan layout results in a poor daylight environment, especially in the middle unit.

According to Table 11, no large difference was shown between the actual building and the notional building in terms of heating and cooling energy consumption and CO_2 emissions; therefore, changing the system may play an important role in this retrofit case.

***Table 11** Thermal performance diagnosis for case 3*

		Actual Building		**Notional building**	**Attained**
Fabric	**Shape Coefficient**	0.27		0.26	☒
	External wall construction	Concrete, Reinforced, 200 mm, EPS Expanded Polystyrene 50 mm, U-value=**0.642** W/ m^2.k		Concrete, Reinforced, 200 mm, EPS Expanded Polystyrene 75 mm, U-value=**0.458** W/ m^2.k	☒
	Roof construction	Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 50 mm, U-value=**0.588** W/ m^2.k		Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 130 mm, U-value=**0.247** W/ m^2.k	☒
	Entrance hall	Double-glazed clear extruded windows (6/13 mm), U-value=**2.665** W/ m^2.k		Double-glazed low-E clear extruded windows (3/13 mm), U-value=**1.786** W/ m^2.k	☒
	Window	Double-glazed clear extruded windows (6/13 mm), U-value=**2.665** W/ m^2.k		Double-glazed low-E clear extruded windows (3/13 mm), U-value=**1.786** W/ m^2.k	☒
	Window to wall ratio	S	0.35	0.35（0.3–0.7）	☑
		N	0.26	0.26（≤0.4）	☑
		E	0.20	0.20（≤0.45）	☑
		W	0.20	0.20（≤0.45）	☑
Energy consumption (kWh/ m^2.yr)		85.26		70.76	☒

4.3.2 Predictive Design

First, the existing residences all had extended bay windows, which increase the external surface area and, consequently, the heat loss. Therefore, the most intuitionistic measure would be to remove the bay windows to gain a reasonable glazing ratio. Figure 10 illustrates the wind environment improvement after retrofit. As a part of the community, each building plays a role in organizing the outdoor air flows, which have a great impact on the built environment and occupant comfort. The reconstructive open ground-floor space in the corner not only reduces the wind velocities on the ground plane outdoors according to the reduced red segments shown in the graphs but also promotes the ventilation in the outdoor activity spaces by weakening the calm zone effect. In the facade design scheme, five wind deflector solutions with different scales and locations were proposed to optimize the wind environment in the top parts of building. The weak spots of different solutions are highlighted by black frames. Following solution 5 of adding several wind deflectors, the general velocity can be reduced to 3.2 m/s, which is the best solution among those verified by simulation.

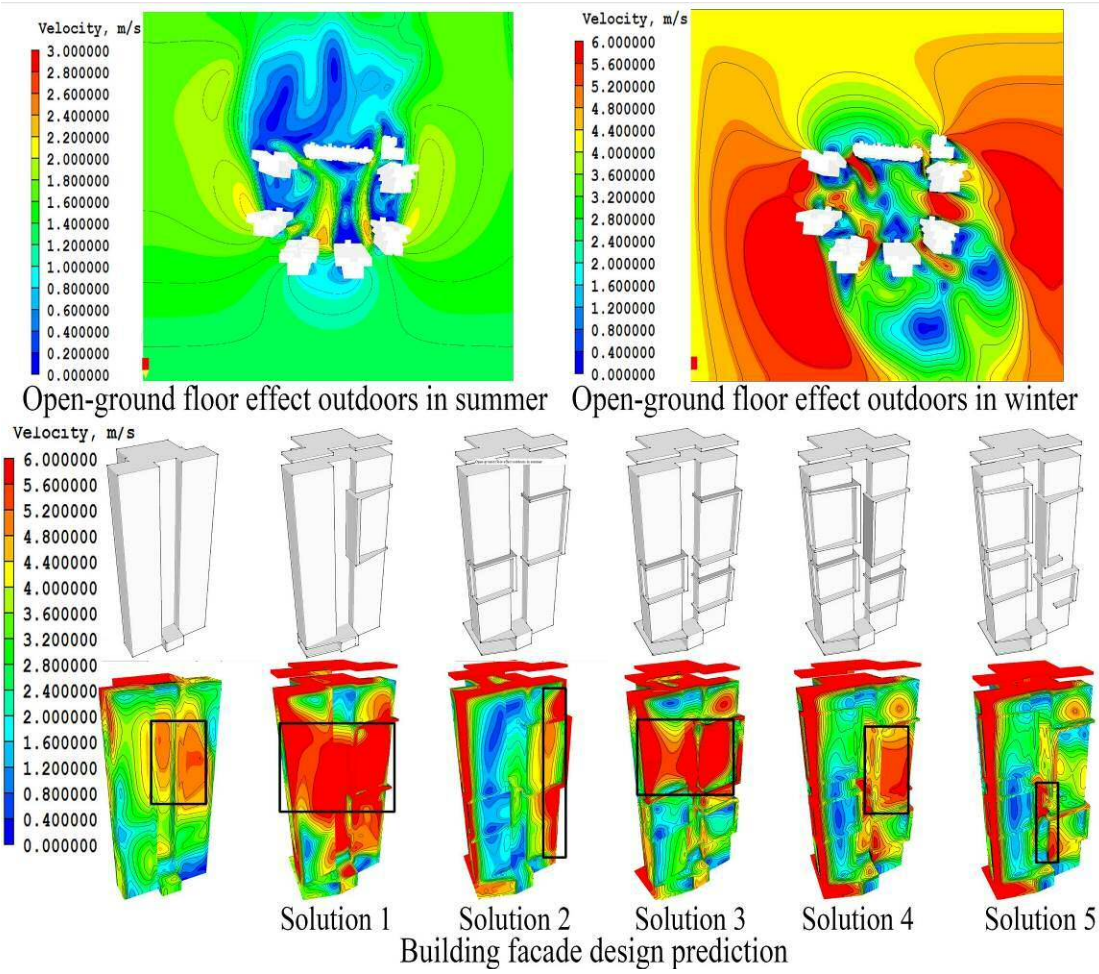


Figure10 *Wind simulation for retrofit design*

As shown in Figure 9, the day light analysis run by Ecotect illustrated that the lighting environment was extremely poor in the middle unit. Figure 11 shows the measures proposed to solve these problems, such as adding blinds with reflective slats to prevent glare and increase the illumination intensity. The adjustable wind deflector is only used on part of the north facade with relatively high wind speeds according to the simulation results.

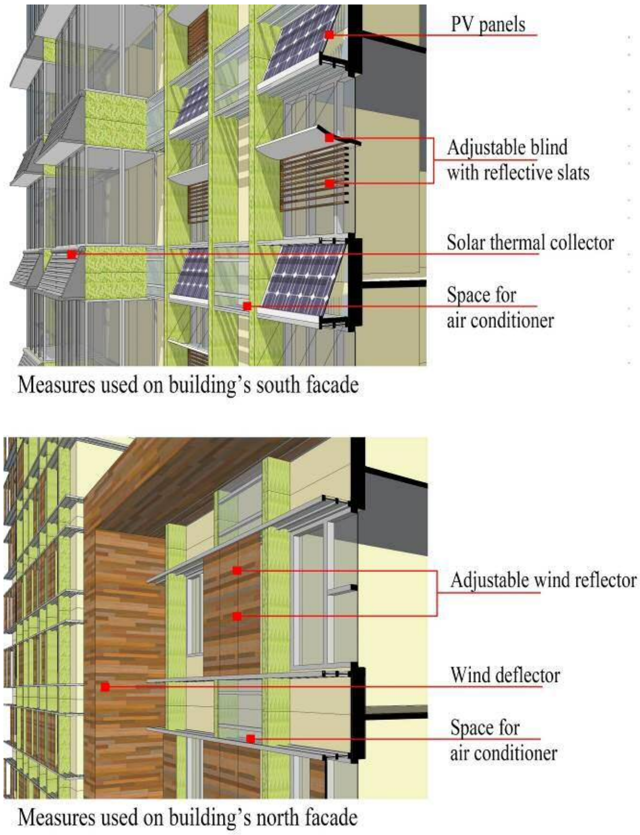


Figure 11 *Visible measures on the building's facades*

Following the discussion and analysis above, 12 measures were tailored to the requirements of the Xinyuancun residence, such as significantly improving the building fabric and adjusting the heating schedule. The performance optimization in relation to the retrofit strategies was predicted and is shown in Table 10. Simulations were run in Designbuilder to determine the building performance before and after retrofit. Table 12 summarizes the energy saving percentages from employing individual elemental design parameters and a holistic approach. The most effective measure in this case is installing solar thermal for domestic hot water heating, which could achieve an energy savings ratio of 9.7%. The holistic retrofit could reduce energy consumption by 36.9% and CO_2 by 44.6%.

Table 12 *Performance optimization prediction for the 2002 Xinyuancun residence in relation to the retrofit strategies*

		Measures	**Details**	**Energy consumption(kWh/㎡·yr)**	**Average savings （%）**	**CO_2（kg/㎡·yr）**	**CO_2 savings （%）**	**Incremental cost （£/㎡）**
Before retrofit								
Actual building		**-**	**-**	**85.26**	**-**	**46.00**	**-**	**-**
After retrofit								
Elemental Design Parameter	**Form Strategy**	Remove bay windows	Remove all of the bay windows	77.20	9.5	44.15	4.0	1.58
		Open ground floor space	Open ground floor space	85.15	0.1	46.09	-0.2	0.27
		Entrance hall	Cavity wall with insulation, Curtain wall with insulation	85.14	0.1	45.97	0.1	0.61
		Reflector and shading	Reflector and shading on south, east and west facades	83.87	1.6	42.78	7.0	2.94
		Wind deflector	Wind deflector on north facade	-	-	-	-	1.31
	Fabric Strategy	External wall insulation	Concrete, Reinforced, 200 mm, EPS Expanded Polystyrene, 75 mm, U-value=0.458 W/ m^2.k	81.38	4.5	45.34	1.4	6.46
		Roof insulation	Concrete, Reinforced, 120 mm, XPS Extruded polystyrene, 130 mm, U-value=0.247 W/ m^2.k	84.72	0.6	45.91	0.2	0.94
		Window	Double-glazed low-E clear windows (3/13 mm), U-value=1.786 W/ m^2.k	81.23	4.7	45.05	2.1	16.28
	System Strategy	Space heating	Sub-metering and room-metering temperature control	79.26	7.0	44.81	2.6	5.15
		Solar thermal	Domestic hot water heating, 308.76 m^2 solar thermal installed on the balconies	77.00	9.7	37.27	19.0	5.33
		Solar PV	Solar electrical energy generation, 93.86 kW photovoltaic panels installed on the roof	84.63	0.7	45.34	1.4	6.57
	Applian ce Strategy	Electric lighting	LED lighting	80.71	5.3	39.36	14.4	1.60
Holistic approach				**53.81**	36.9	**25.48**	44.6	49.04

5 SUMMARY AND DISCUSSION

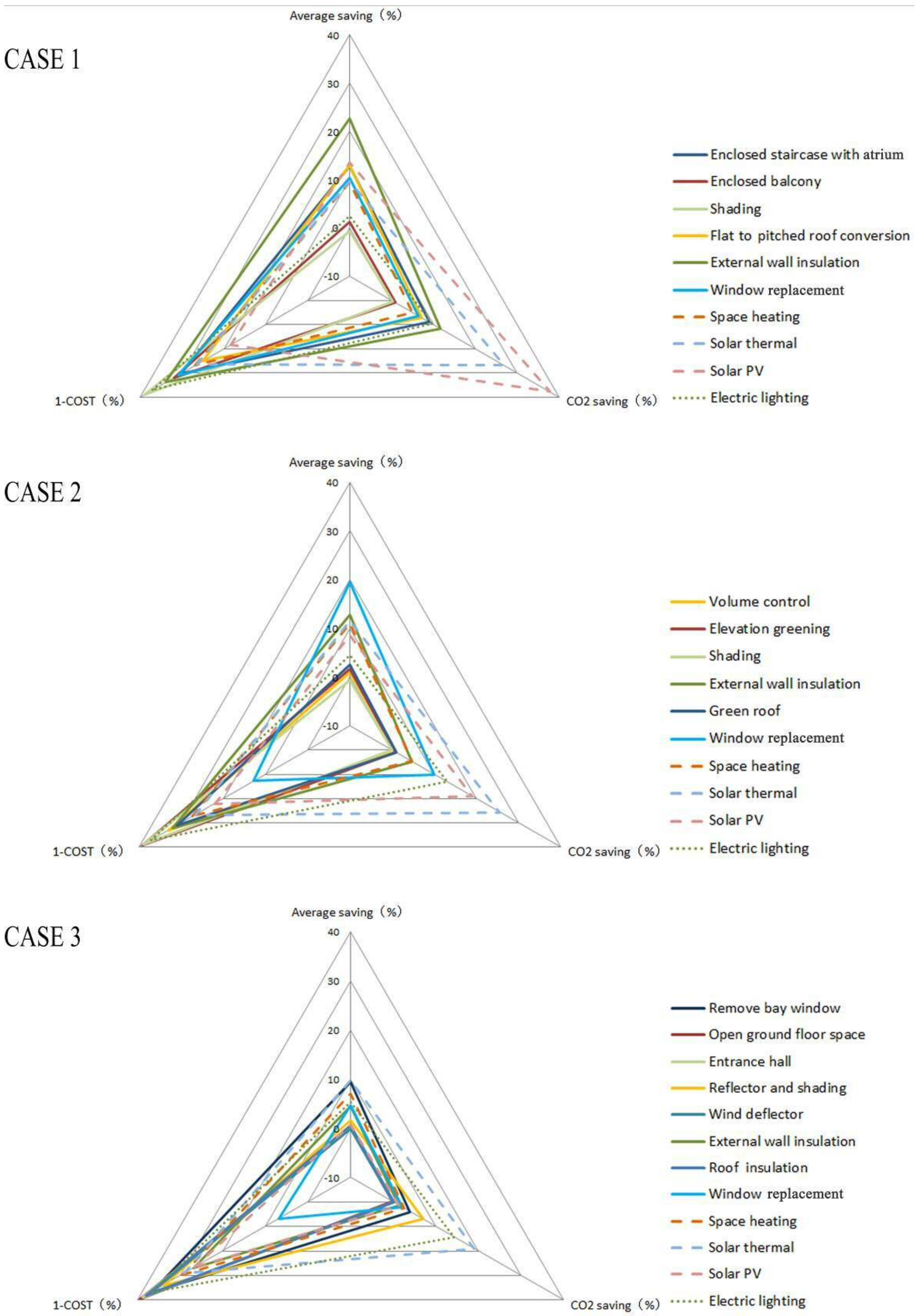


***Figure 12** Radar diagram analysis for 3 cases*

Different priorities of retrofit options for each residence can be identified considering different footholds. As shown in Figure 12, the radar plots give the results for the energy savings rate (%), the CO_2 emissions savings rate (%) and the cost capability (%) to visualize the elemental retrofit effect combing these three indicators. Screening and grouping strategies at the early stage is necessary.

EWI, solar thermal and space heating schedule change show considerable improvements in energy consumption for all three cases. Solar PV and WinR could be used on buildings in the 1981 and 1995 age cases but not the 2002 case due to low cost performance. Some measures such as enclosed staircases, solar shadings, open ground floor spaces, winter deflectors that mainly target environment comfort do not greatly increase energy consumption. The effect of a holistic combination of all of the strategies isn't equivalent to the sum of effect of every single measure's effect. However, this simulated data can guide the selection of retrofit measures for these three different building types in the case of limited funds.

The process followed here is just a preliminary decision-making step towards different retrofit goals. The building performances before and after a holistic retrofit are summarized and compared in Figure 13. The older the residence is, the greater the low-carbon or low-energy retrofit potential is. The 1981 case shows the greatest energy savings and CO_2 savings with a low incremental cost. However, the 2002 high-rise case shows more challenges in performance optimization and a high incremental cost. Domestic retrofit could gain a prominent achievement both in reducing energy consumption and improving architectural aesthetics (Figure 14).

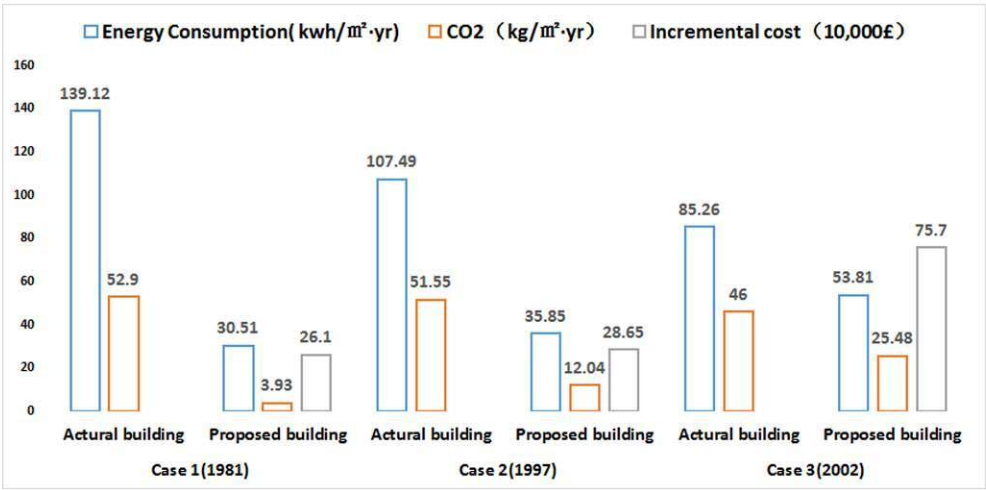


Figure 13 *Performance optimization prediction before and after a holistic retrofit approach*

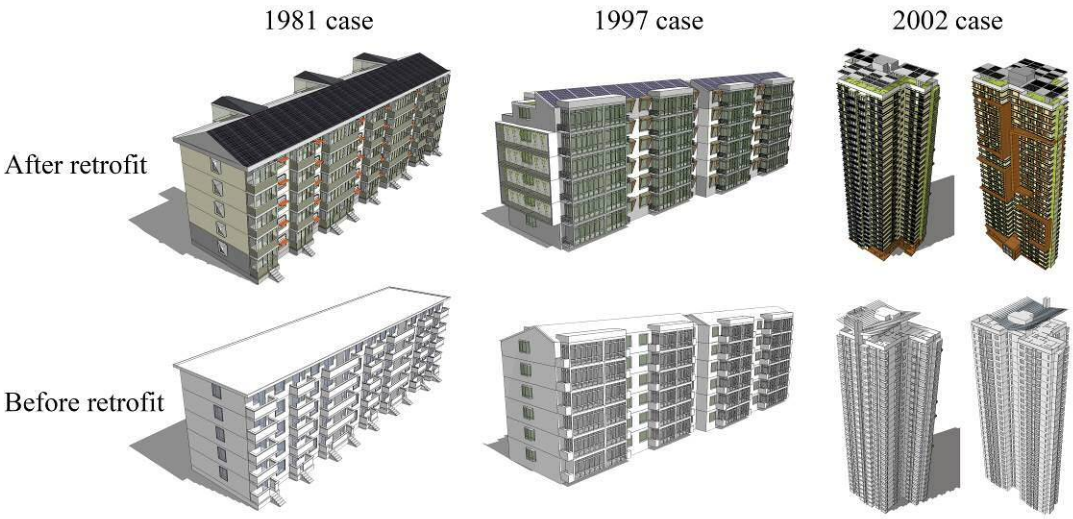


Figure 14 *Appearance comparison before and after retrofit*

6 CONCLUSION

A number of issues should be considered in the decision making of domestic building retrofits. Performance diagnosis first identifies issues in the physical built environment and examines building energy consumption and CO_2 emissions before a retrofit. Comparative analysis can tailor the holistic approach. The design procedure is a reproducible method, especially for designers who lack knowledge of building physics. With the help of a simulation tool, retrofitting China's contemporary housing stock can be taken as a performance-priority optimization to achieve balances among energy consumption, occupant comfort and investment.

The three cases here are examples of different housing types. Measures should be selected in response to different budget concerns. When designed properly, the application of a single strategy could achieve an energy savings ratio of up to 22.7% and a CO_2 reduction ratio of 11.7%. Combining different measures in a reasonable way may also reduce costs. Hence, different retrofit routes and corresponding priorities should be applied towards different conditions and for different purposes.

Due to the limitation of time, non-unified standards and construction reality, fully-integrated design is different to cover all aspects. Thus this research tends to solve issues only associated with individual building performance and appearance at the early stage without taking acoustics, durability and other uncertain information into account. Widely interdisciplinary investigation and cooperation are in great demand to aid domestic retrofit practice. For future work, a large number of solutions will be modelled under the same simulation environment and the results will be validated by monitoring the real buildings.

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