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Energy-Efficient Window Retrofit for High-Rise Residential Buildings in Different Climatic Zones of China

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Abstract: The building envelope plays a significant role in the energy performance of buildings and windows are a key element in transmitting heating and cooling between the indoor and outdoor environment, and hence an adequate window system is one of the most important retrofit strategies of existing buildings for energy conservation. Therefore, this study presents a method with a theoretical case study to examine the improvement of energy efficiency in a typical high-rise residential building through window retrofitting. A building energy design model in Designbuilder along with a building information modeling (BIM) model in Revit are developed, with 20 common potential glazing alternatives being analyzed to predict the potential energy savings in the same case building with identical orientation located in a variety of climate zones in China. Based on different parameters and considerations, the results demonstrated that the currently relatively expensive low-e window glazing has the best energy performance in all climate zones, but is sufficiently close to conventionally glazed windows in its energy efficiency to discourage its adoption at present, and that, instead, a single dark conventional glazed window is preferred in a hot summer/warm winter climate, double dark traditional glazing in a hot summer/cold winter climate, and a double clear conventional window in a cold climate. Based on the simulated results, an indicative suggestion was provided to select an adequate window system for residential building retrofitting in the studied climates or similar climatic regions.

Keywords: window retrofit; energy simulation; energy saving; high-rise residential building; climate zones

1. Introduction

Energy consumption in buildings accounts for about 40% of global energy use [1], of which space heating and cooling consumes approximately 60% [2]. It is not surprising, therefore, that heating and cooling loads are the largest energy consumers in residential buildings [3,4] and that reducing the demand for heating and cooling is critical for saving energy [5]. Meanwhile, energy use is increasing rapidly worldwide. The rate of energy consumption in China, for example, is expected to increase by an average of 7.4% over the next 10 years [6], with the total energy demand in buildings increasing by 110–150% by 2050 and 160–220% by 2095 from the 2005 level [7]. Therefore, many governments and organizations have committed to reduce energy consumption by improving energy efficiency in existing buildings [8]. Numerous studies have compared energy consumption forecasting in building based on different forecast engines [9–11].

Notably, China is the world's largest energy consumer generally, second largest for all buildings and largest for residential buildings [12]. The total building stocks in China was estimated to be around 44 billion m^2 by the end of 2005 [13], which should have increased to over 50 billion m^2 in 2010 and will reach around 58 to 78 billion m^2 by 2050 [14]. The lifetime of buildings in China ranges from 50 to 75 years [15–18]. Therefore, the government has set a national standard for the energy performance of existing residential buildings that requires their energy consumption to be reduced by 50% while still providing the same level of indoor comfort [15]. In order to reach this target, the government has emphasized the importance of retrofitting residential buildings for energy conservation and has made some efforts to upgrade them in recent years [19,20]. While high-rise residential buildings account for a large proportion of the building stock and due to the need to adopt energy-efficient design and materials for this type of building, introducing sustainable retrofit to high-rise residential building should therefore help reduce the energy consumption and hence achieve the emission reduction targets of a country or city [21].

The renovation of existing buildings has attracted increasing attention globally, as retrofitting enhanced building energy efficiency, reduced energy consumption and CO_2 emissions [22–24], but optimal strategies should be identified in building renovations [25,26]. An adequate window glazing system is one of the most important retrofit strategies for effective energy conservation of a building, as the U-value and solar heat gain coefficient (SHGC) of windows have great impact on the heating and cooling demands of buildings [8].

The thermal properties of the building envelope have a significant impact on building energy performance [27], as a significant amount of energy is used to compensate for heat transferred through this building feature. Windows play an important part in this since heat transmittance through windows is five times larger than other components of the building envelope, with the energy lost in this way being up to 40% of the total building energy consumption. Meanwhile, the solar heat gain which can increase the indoor cooling demand in non-cold regions and help reduce the heating demand in cold regions is primarily through windows. Window glazing makes a significant contribution to the heating and cooling demands of buildings [28], the main energy load being the heat transfer through window glass [29]. Heating, ventilation, and air-conditioning (HVAC) is most important consideration in building energy performance, as these are responsible for the largest part of energy consumption [30]. The use of window systems including coatings, light reflection, and transmittance have a great impact on the energy consumption of building. Thus, the shading coefficient of windows should remain low in hot climate areas, because it may increase the cooling load due to solar radiation. However, solar energy can decrease the energy consumption in cold regions [31]. The wall window ratio (WWR) and the window type may have a positive effect due to solar gain and daylight duration during winter, but it could lead to cooling demand during summer in hot climate zones [32]. Moreover, the cooling demand is increased due to the multiple reflections of radiation heat flux, as it can significantly increase the air temperature surrounding the buildings [33]. Optimization of indoor environmental quality and energy efficiency for different types of facades by considering various properties like thermal, solar, luminous, and so on is now an ongoing research topic [34]. Although light-colored external surfaces are conceived to have better energy performance, depending on different climatic zones [30], thermo-chromic glazing can improve the energy performance and visual comfort [35]. It is, therefore, important to measure the visual impacts and energy performance of windows due to the use of different glazing systems and coatings such as clear float glass, double-glazed windows, low-e glass, electrochromic, etc., based on different climatic zones [36]. Therefore, the use of higher energy efficiency window glazing provides an important means of saving energy [37]. As a result, many recent publications are related to the use of energy efficient windows to improve the building performance. Some studies emphasize the relationship between window thermal properties and building energy performance, focusing on a window's inherent characteristics such as the U-value, SHGC, window wall ratios, and window direction [38]. They usually calculate and analyze the absolute energy reduction brought about by a certain type of window glazing. According to the direct amount of energy saving, the most common alternative glazing is low-e glass [39,40]. Others analyze the advantages of using advanced glazing systems with low-e features such as photovoltaic and smart windows to reduce the energy consumption [41–46]. In addition, Deb and Lee [47] analyzed the main influencing variables of building energy consumption in office buildings in Singapore based on pre- and post-retrofit data. Ginks and Painter [48] conducted a perceptional study using a web-based survey targeting professionals in the energy sector to analyze the energy retrofit measures in historic buildings through window retrofit to slim profile double-glazing in the UK. In addition, the effects of window glazing on daylight and energy consumption were evaluated by Hee et al. [49], while the energy saving potential through retrofitting was examined by Fasi and Budaiwi [50].

Most of the abovementioned studies refer to the window orientation and wall-window ratios when choosing a type of window glazing, with little consideration of the climatic zone involved in the study region, specifically focusing on window retrofitting. While buildings in hot regions necessitate cooling whereas those in cold regions need heating, the universally recommended low-e glazing by previous studies may not always be the best answer for energy saving in specific climatic conditions and it is necessary to consider the relationship between the climate and window glazing in search for higher energy performance.

Therefore, this study aimed to identify the most energy efficient window glazing upgrading measures for high-density high-rise residential buildings in a variety of climatic conditions in China. In this study, a computer-based simulation combining the strengths of building information modeling (BIM) and energy analysis was conducted to evaluate the effect of alternative window glazing types on total building energy load from a model based on an existing residential block with building characteristics typical of high-density high-rise residential buildings. This was then applied to three specific areas of hot summer/warm winter, hot summer/cold winter, and cold climates in China, as typified by Hong Kong, Shanghai, and Beijing, respectively. It is expected that the results of this study can be used for selecting an appropriate window glazing system for residential buildings at the time of retrofitting so as to maximize the energy conservation under different climatic conditions.

2. Method

The purpose of the study is to identify the best form of energy-saving window glazing for high-rise residential blocks for different climatic regions in China. This involves the use of the DesignBuilder software integrated with a BIM model established in Autodesk Revit to simulate the energy consumption involved in heating and cooling of a typical high-density residential building block in representative cities of the main climate zones (i.e., hot summer/warm winter, hot summer/cold winter, and cold climates in China). The detailed information of climatic zones and cities are given in the Supplementary Information. BIM facilitates the access of comprehensive building data such as building components and their properties during the whole building life cycle [51,52]. BIM-based Autodesk Revit is very useful for modeling, simulating, and optimizing performances [53–55]. DesignBuilder is one of the most widely used building energy efficiency measures and optimization tools [56]. The main research process involves:

(1) identifying the climate zones and their representative high-density cities;
(2) choosing a typical high-rise residential block as a base for modelling and collecting the data needed for its modelling and simulation;
(3) building a BIM model of the block in Autodesk Revit and base energy model in DesignBuilder from the data gathered;
(4) selecting a variety of window glazing types for comparison with the traditional window glazing used;
(5) simulating the heating and cooling loads of the block for each window glazing type in each climate zone;

(6) analyzing the energy consumption involved and conducting a data analysis involving such thermal properties as U-value and SHGC; and
(7) comparing the energy savings predicted from the different types of window glazing and finding the best type for each climate.

This involved a variety of data collection methods, including accessing government records, emails, telephone calls, face-to face interviews, use of a site survey and other fieldwork, computer-based simulation, and comparative analysis for the prediction of energy savings from each glazing type. The major study processes are shown as in Figure 1.

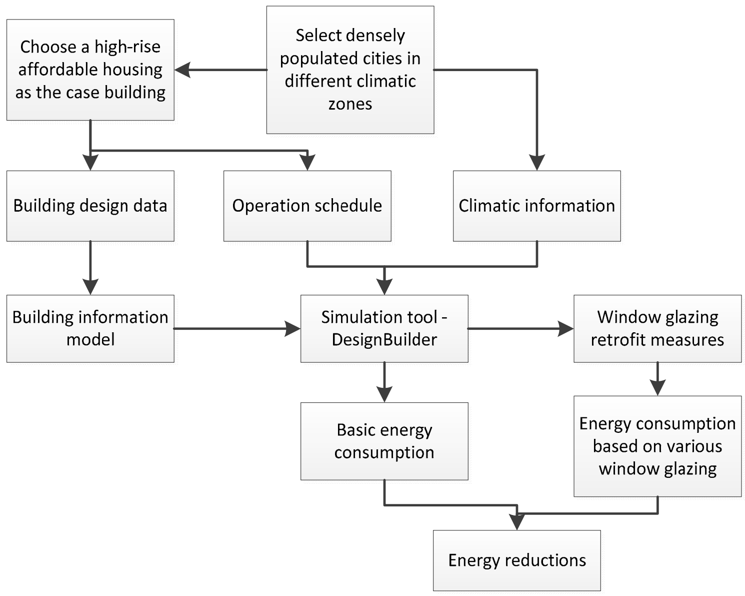

Figure 1. Flowchart of the major study processes.

A key aspect of this research is the base block for computer simulation. This is a typical high-density high-rise residential building in Hong Kong as it shares similar features of the high-density high-rise residential buildings in major cities of China under different climatic zones. This enabled energy simulation to be conducted to identify the impact of energy performance based on the same building characteristics but under different climatic conditions. It was modelled and simulated by the energy analysis tool based on its traditional single sheet clear glazing to provide the baseline for energy consumption and to measure the energy savings resulting from other options. These options were put into the energy analysis model individually and the corresponding simulations conducted to predict the energy performance of the whole building. This involved:

(1) modeling in Autodesk Revit and DesignBuilder;
(2) validating the base energy model with the energy consumption results of previous studies;
(3) the use of alternative window glazing to compare with the traditional window design; and
(4) hundreds of iterations simulating the energy reduction of the building model for each type of glazing.

It has already been mentioned that the three high-density cities involved were Hong Kong, Shanghai, and Beijing, representing hot summer/warm winter, hot summer/cold winter, and cold climates, respectively.

3. Base Case

3.1. The Building

Over 90% of the population in Hong Kong lives in high-rise residential buildings, of which an estimated more than 50% were built 20 years ago [57]. The basic configuration of high-rise building envelopes is the same in the three cities, and therefore, one generic high-rise residential building was chosen (with same orientation) to simulate its individual energy performance when located in Hong Kong, Shanghai, and Beijing, which indicates there is no difference between the models in the selected cities except for location and climate.

The base case is a 20-story Hong Kong residential block built over 20 years ago. It is southeast oriented, as that is the popular direction for ordinary residential buildings in China due to geographic location and its energy saving potential [58]. The shape of the building maximizes the number of flats on each floor to make good use of the limited amount of land available. This has become the dominant layout for high-rise residential buildings to meet the dramatically increasing housing demand over the past 30 years. The window system of the case building is aluminum framed with 6 mm single clear sheet glazing. The window-wall-ratio is around 30%, with no special shading outside the window.

The key building service element is the heating, ventilation, and air-conditioning (HVAC) system, which comprises a single air conditioner unit. The primary building energy loads (such as from lighting, cooking, computers, and other miscellaneous equipment) occur in the morning and night. Although some buildings in Beijing have boilers for space heating, it is assumed for the purposes of the simulations all have the same dependency on a single HVAC unit.

3.2. Data Collection and Site Survey

The data needed for the energy analysis included building characteristics consisting of geometry, layout, envelope, construction, energy loads, and building service systems such as HVAC, lighting, and the operation schedule involved. These were collected based on the existing building drawings and documents. No electronic information was available and only hard copies of 'as-built' blueprints were permitted to be taken away for study. Additional detailed information not contained in the public documents was obtained through emails, telephone calls, and face-to face interviews.

Despite this, there was still a shortage of data to build the BIM and energy models as most existing high-rise buildings were erected about 20 years ago and there was a lack of information about their specific design, alterations, maintenance, or renovation. Site surveys were, therefore, carried out to further identify the characteristics of the base building, such as the use of materials, dimensions of different building elements or components, installation methods, etc., in order to meet the input requirements for energy simulation. In the absence of certain design parameters, the researchers had to rely on the default values of the energy analysis tool such as the clothing schedule definition; thermal resistance of occupants' clothing; return air fraction and radiant fraction and visible fraction of general lighting; latent/radiant fraction of catering; miscellaneous equipment; and so forth, or the data found in previous studies to conduct the energy simulation.

3.3. Building Data

The main characteristics of the model are summarized in Tables 1–3. Typically, as with such blocks in non-severe climatic regions, it has no wall insulation. The occupants always go home after they finish work or school, so the operation schedule is from 4 p.m. to 8 a.m. All the elevators work non-stop. There is no shading system provided, the only shading being an indoor curtain. The HVAC system is the major source of energy consumption, with the energy use for air conditioning accounting for the largest proportion. The common set point for indoor temperature is 20 °C in winter and 25 °C in summer. One of the most cost-effective methods to save energy is by setting the temperature back while the building is not occupied. The common set back temperature for a time period is from 3 to 10 °C when the space will not require as much heating or cooling [59–61]. It was assumed that thermostats were set back 5 °C in the study when there is no occupant at home. Hence, the heating setback setpoint was 15 °C in winter and the cooling set back temperature was 30 °C in summer as shown in Table 3. In hot conditions, the air conditioning is used from around 4 p.m. to 11 p.m. in order to reduce energy consumption, while in cooler conditions, because of the lower natural temperature during the nighttime, the daily operation period of heating tends to be from 6 p.m. to 8 a.m. in winter. The average infiltration rate in existing high-rise residential buildings is around 0.5 ach^{-1} in Hong Kong according to previous studies and literature [62–65].

Table 1. Primary building loads.

Consideration	Occupancy Density (People/m^2)	General Lighting Power Density (W/m^2)	Computer Load (W/m^2)	Cooking Equipment (W/m^2)	Miscellaneous Equipment (W/m^2)
Building load	0.1	0.6	2	7	4
Operation schedule	24 h	6 a.m.–8.a.m. and 4 p.m.–11 p.m.	6 a.m.–8.a.m. and 4 p.m.–11 p.m.	6 a.m.–7. 30 a.m. and 5 p.m.–8 p.m.	24 h

Table 2. Thermal properties of the building envelope.

Category	Construction	U-Value (W/m^2·k)	SHGC
Exterior wall	5 mm beige stucco (outermost side) 30 mm cement plaster 200 mm medium-weight concrete block 30 mm cement plaster (innermost side)	1.868	No
Interior wall	20 mm cement plaster 150 mm medium-weight concrete block 20 mm cement plaster	1.942	
Roof	10 mm clay tile 30 mm cement plaster 50 mm polyurethane foam 1 mm bitumen sheet 20 mm cement plaster 150 mm reinforced concrete 20 mm cement plaster	0.471	
Upper floor	10 mm cement plaster 200 mm reinforced concrete 10 mm cement plaster	2.470	
Ground floor	20 mm cement plaster 170 mm reinforced concrete	3.038	
Door	Wooden flush panel hollow core door 6 mm plywood panel 27 mm air gap 6 mm plywood panel	2.498	
Window glazing	6 mm single generic clear glass pane; Aluminum window frame; Main window height: 1500 mm Main sill height: 900 mm Main window width: 1200; 1500; 1800 or 2100 mm	5.78	0.819

Table 3. Heating, ventilation, and air-conditioning (HVAC) parameters.

Consideration	Heating	Cooling	DHW (Domestic Hot Water)	Natural Ventilation
HVAC facilities	Unitary air conditioner	Unitary air conditioner	Individual electricity water heater	/
Setpoint (set back)	20 °C (15 °C)	25 °C (30 °C)	65 °C	Min fresh air per person
Operation schedule	24 h during heating months	1. p.m.–7 a.m. during cooling months	24 h on, with 2.45 L/m^2·daily consumption rate	24 h in non-air conditioning time period

3.4. Window Glazing

The most common types of window glazing are incorporated into single-glazed and double-glazed windows, involving clear/tinted generic/low-e glazing [66].Therefore, this study focused on the energy savings resulted from the use of various single/double-glazing alternatives of different thicknesses, glass pane types, and colors. Single tinted glazing has a certain impact on reducing the solar heat gain and it is an optimal window glazing choice in the warm climate zones when considering the energy savings and the costs of window retrofit. Double-glazing is also increasingly used in the cooling-dominant regions. In the heating-dominant zones, the most common window system for energy conservation is double- or triple-glazing with vinyl frames [67]. In many sustainable retrofit projects in northern China as referenced by the EEEB, 6/6 mm and 6/13 mm double-glazing systems and are often utilized for energy efficiency improvements in Beijing, Urumqi, Tangshan, and Harbin [68–71]. In the hot summer and cold winter zones and the cooling-dominant zones, it is better to install the 6/12 mm double-glazing or the 6/12 mm low-e glazing on windows due to their energy performance in those zones [72]. Single low-e glass may be used to reduce the cooling demand in the cooling-dominant regions without causing any glare like the reflective glazing [73]. The 6 mm single low-e glazing has much better energy performance than other general glazing of the same thickness and it is, therefore, a proper measure to reduce building energy consumption in the warm zone [74]. Given the trends in China in recent years, the present study selected three major types of glazing for analysis, i.e., 6 mm single low-e glazing with different colors; 6/6 mm double-glazing with air or argon sealed with various colors based using the generic or low-e panes; and 6/13 mm double clear or tinted window with generic and low-e glass clear glazing, to explore the suitability of various window glazing systems for different climatic zones. The window glazing alternatives for sustainable retrofit of existing residential building cover a wide range of conventional and advanced window systems with diverse thermal properties. Both high and low thermal transmittance were taken into account in the present study. The two main thermal properties of windows are the U-value and SHGC. The U-value represents the thermal transmittances through the glazing, which is usually used to measure how effective it is as an insulator. SHGC is the fraction of incident solar radiation admitted though a window. This study did not consider thermal bridge, although energy exchange through thermal bridges is an important consideration for energy performance of windows, as it may influence the energy consumption, thermal comfort, and durability of building envelope [75–77]. Moreover, the energy simulation tool DesignBuilder does not consider thermal bridge during its calculation and the impact of thermal bridge on the calculation of energy consumption in DesignBuilder is restricted in some preconditions such as certain range of wall thickness [78].

Table 4 details the 20 types of window glazing used in the simulations. They are classified into three groups of 6 mm single-glazing, 6/6 mm double-glazing with 6 mm air or argon filling, and 6/13 mm double-glazing with a 13 mm air-sealed cavity. The single clear glazing with 6 mm generic glass was based on the original window design of the base building and is the dominant type of window glazing in existing old high-rise residential building in China. Its U-value (5.778 W/m^2·k) and SHGC (0.819) are the highest of all the glazing types and therefore has the most heat transmittance and heat gain. The low-e window is well known for its better thermal performance and both its U-value and SHGC are the lowest. Tinted glass has a relatively low SHGC and is beneficial in reducing solar heat gain. For double-glazing, the thickness and type of filled gas between the two glass panes is likely to affect thermal performance and was selected with a 6 or 13 mm thick air or argon layer to distinguish their energy performance. Currently, the fenestration market is dominated by air or argon filled double-glazed windows due to their good thermal insulation performance compared to conventional single-glazing with their well fabrication process [79]. Various studies have adopted the air or argon filled different window glazing systems for thermal performance investigation (e.g., Cuce et al. [80]).

Table 4. Thermal properties of three groups of window glazing.

	Group S: 6 mm single-glazing				
	Sc: Clear	Sg: Grey	Sb: Blue	Sl-c: Clear low-e	Sl-t: Tinted low-e
U-value (W/m^2·k)	5.778	5.778	5.778	3.44	3.44
SHGC	0.819	0.602	0.62	0.637	0.45
Daylight transmittance (%)	88	43	57	81	50
Description	Window frame: aluminum; glass type: 6 mm generic or generic low-e glass				

	Group D: 6/6 mm double-glazing with 6 mm filled gas									
	Air filled					Argon filled				
	Da-c: Clear	Da-g: Grey	Da-b: Blue	Dal-c: Clear low-e	Dal-t: Tinted low-e	Dg-c: Clear	Dg-g: Grey	Dg-b: Blue	Dgl-c: Clear low-e	Dgl-t: Tinted low-e
U-value (W/m^2·k)	3.09	3.09	3.09	2.43	2.43	2.829	2.829	2.829	1.99	1.99
SHGC	0.7	0.485	0.503	0.569	0.398	0.702	0.481	0.499	0.568	0.388
Daylight transmittance (%)	78	38	50	72	44	78	38	50	72	44
Description	Window frame: aluminum; glass type: 6 mm generic glass for traditional window, 6 mm coated glass for low-e glazing; filled window gas: 6 mm air or argon									

	Group DT: 6/13 mm double-glazing with 13 mm filled air				
	DT-c: Clear	DT-g: Grey	DT-b: Blue	Dtl-c: Clear low-e	Dtl-t: Tinted low-e
U-value (W/m^2·k)	2.66	2.66	2.66	1.76	1.76
SHGC	0.703	0.478	0.497	0.568	0.38
Daylight transmittance (%)	78	38	50	72	44
Description	Window frame: aluminum; glass type: 6 mm generic glass for traditional window, 6 mm coated glass for low-e glazing; filled gas: 13 mm air				

3.5. Modeling

Figure 2 shows the 3D BIM model of the base building and its floor layout after inputting all the required data into Autodesk Revit. This was exported into a gbXML file and combined with DesignBuilder to build the base energy model in order to estimate the building's basic energy consumption. The five main categories of assumptions involved in this are (i) lighting system: this involves lamps, ballasts and luminaries, and the normal power density of indoor lighting, with information coming mainly from the design plans and previous related studies; (ii) the HVAC system: the type of air conditioner, heating and cooling set points, supply temperature, air distribution plan, coefficient of performance (COP) for heating/energy efficiency ratio (EER) for cooling; natural ventilation designs such as outside air flows and operation schedule; (iii) domestic hot water (DHW): type of electric water heater, consumption rate, water temperature, delivery temperature, operation schedule; (iv) building loads: occupancy density, computer, cooking and miscellaneous equipment; and (v) operation schedule: for lighting, air conditioning, occupancy, DHW, and building loads. The 3D energy model in DesignBuilder is also shown in Figure 2.

To validate the model, we compared the simulated average annual electricity consumption of the base model with traditional glazing of approximately 160 kWh/m^2 with the actual consumption. The most common evaluation of electricity use in high-rise blocks was around 110 kWh/m^2 in 2004 [81,82]. Taken together with the average annual rate of increase of electricity use in residential buildings in Hong Kong of 3.7% per unit area [83,84], this gives an estimation of 164 kWh/m^2 for 2015, which is considered close enough to the simulated result.

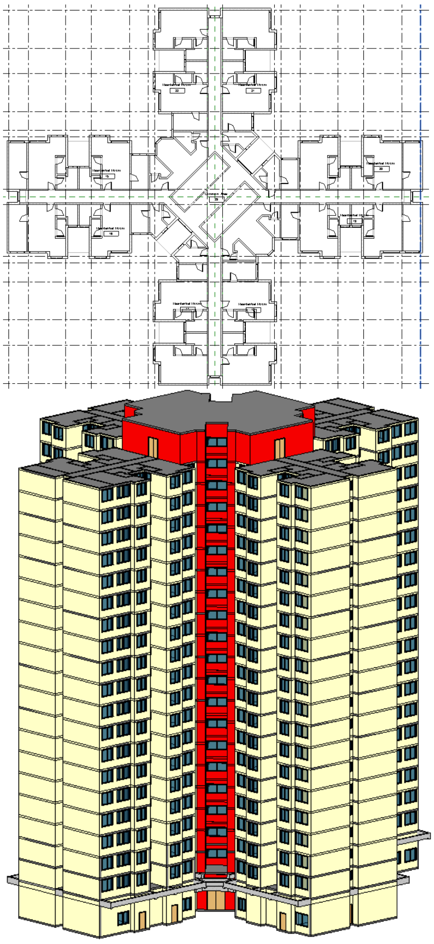

Figure 2. 3D building information modeling (BIM) model and its floor layout.

4. Simulation Results

The results of the simulations in terms of annual energy savings (due to heating and cooling) per unit area over the traditional single sheet clear glass window for Groups S, D, and DT in the three climate zones are depicted in Figures 3–5. Note that the alternative forms of glazing affect the energy consumption of heating and cooling but cannot affect the energy use of appliances, domestic hot water, lighting, and other facilities. Therefore, we focused solely on the change in heating and cooling loads due to the various glazing options.

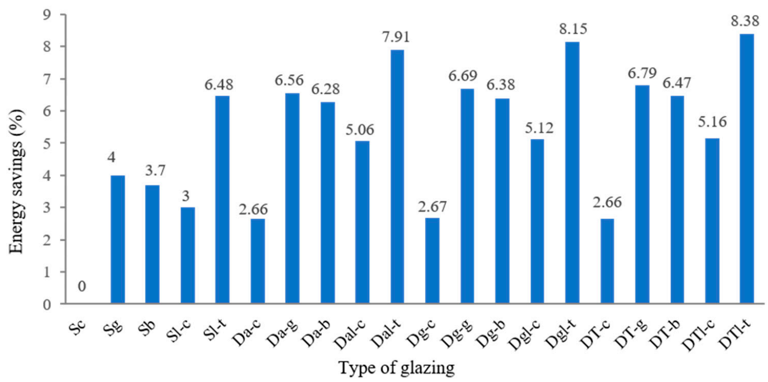

Figure 3. Energy reduction from glazing types in Hong Kong. (Group S: 6 mm single-glazing; Group D: 6/6 mm double-glazing (Da: air filled, Dg: gas filled); Group DT: 6/13 mm double-glazing with 13 mm filled air).

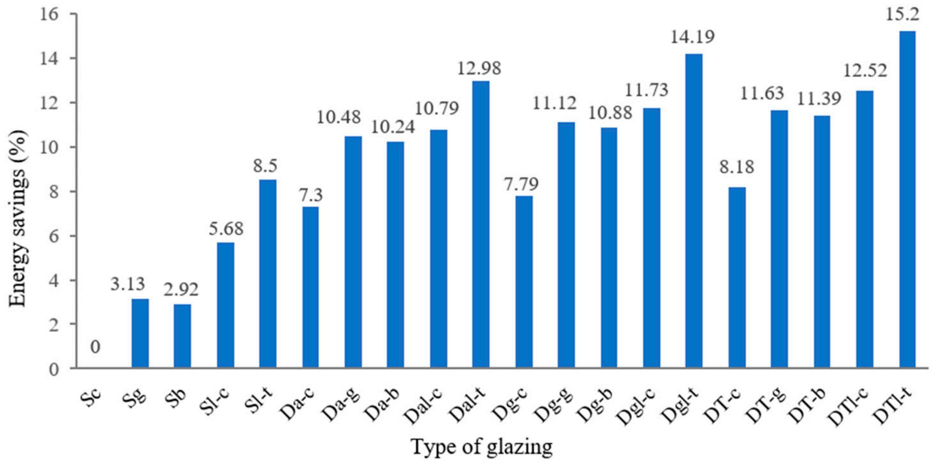

Figure 4. Energy reduction from glazing types in Shanghai.

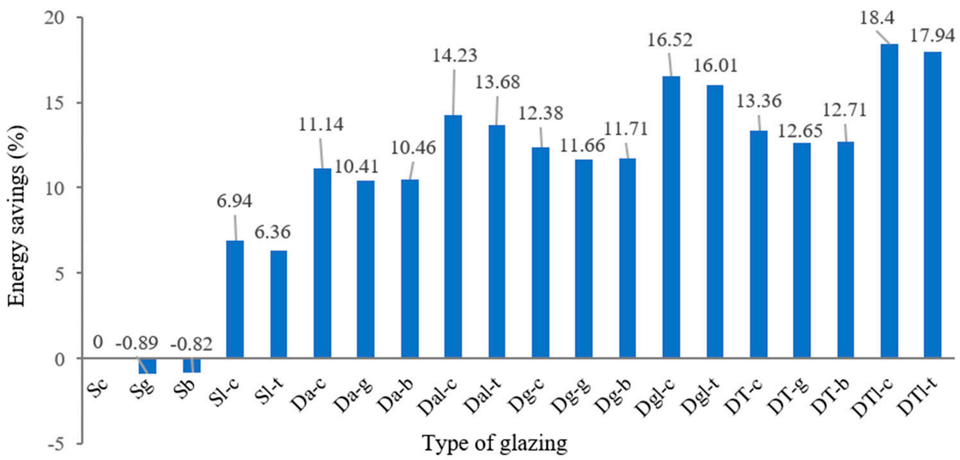

Figure 5. Energy reduction from glazing types in Beijing.

4.1. Window Glazing in the Hot Summer/Warm Winter Climate

Figure 3 shows the energy reduction in Hong Kong's hot summer/warm winter climate, indicating that the tinted low-e glass (-t) has the best energy performance in each group. Of the ordinary double-glazed windows, Da-g, Dg-g, and DT-g have a better energy performance with similar savings of 6.56% (i.e., 2.04 kWh/m^2/year including a cooling reduction of 2.04 kWh/m^2/year and a heating reduction of 0 kWh/m^2/year); 6.69% (i.e., 2.08 kWh/m^2/year including a cooling reduction of 2.08 kWh/m^2/year and a heating reduction of 0 kWh/m^2/year); and 6.79% (i.e., 2.11 kWh/m^2/year including a cooling reduction of 2.11 kWh/m^2/year and a heating reduction of 0 kWh/m^2/year), respectively. Double air thickness is therefore not important for energy consumption in this climate. Similarly, the type of gas filling has relatively little effect. For the 6 mm ordinary single-glazing, the single grey window (Sg) has the best energy saving at around 4% (i.e., 1.25 kWh/m^2/year). Even though its performance is less than double-glazing, it still can reduce cooling demand significantly in this climate.

4.2. Window Glazing in the Hot Summer/Cold Winter Climate

The simulated energy savings for Shanghai's hot summer/cold winter climate, where both domestic heating and cooling is needed to maintain indoor thermal comfort, are given in Figure 4. As with Hong Kong's climate, the low-e glazing produces the largest energy reduction in 6 mm single windows (group S), 6/6 mm (group D) double air or argon filled glazing, 6/13 mm double window with air-sealed cavity (group DT). As shown in Figure 4, the ordinary windows Da-g, Dg-g, and DT-g have a similar energy reduction at 10.48% (i.e., 3.58 kWh/m^2/year including a cooling reduction of 2.48 kWh/m^2/year and a heating reduction of 1.10 kWh/m^2/year), 11.12% (i.e., 3.80 kWh/m^2/year including a cooling reduction of 2.48 kWh/m^2/year and a heating reduction of 1.32 kWh/m^2/year) and 11.63% (i.e., 3.97 kWh/m^2/year including a cooling reduction of 2.47 kWh/m^2/year and a heating reduction of 1.50 kWh/m^2/year), respectively. For the 6 mm single-glazing, its largest energy saving is 3.13% (i.e., 1.07 kWh/m^2/year including a cooling reduction of 1.84 kWh/m^2/year and a heating increase of 0.77 kWh/m^2/year), which is far less than the double-glazed windows.

4.3. Window Glazing in the Cold Climate

Figure 5 reflects the energy savings produced by the various glazing forms in Beijing's cold climate, where heating is the dominant source of energy consumption. In this case, clear double-glazing has the best thermal performance irrespective of its thickness, with low-e glazing providing the largest energy reduction. The energy performance of ordinary windows is quite similar, with the 6/6 mm double-glazing group D producing the largest energy reduction of 11.14% (i.e., 3.42 kWh/m^2/year including a cooling reduction of 0.34 kWh/m^2/year and a heating reduction of 3.08 kWh/m^2/year) caused by traditional double-glazing Da-c compared with the 14.23% (i.e., 4.37 kWh/m^2/year including a cooling reduction of 0.72 kWh/m^2/year and a heating reduction of 3.65 kWh/m^2/year) produced by the low-e glazing Dal-c in the same category. Next to the 6/6 mm double clear low-e glazing (Sl-c, Sl-t, Dal-t, Dgl-c, Dgl-t, DTl-c, Dtl-t), the best energy saver is the clear double-glazing with 13 mm filled air (DT-c) at 13.36% (i.e., 4.10 kWh/m^2/year including a cooling reduction of 0.30 kWh/m^2/year and a heating reduction of 3.80 kWh/m^2/year), followed by another form of clear double-glazing with a 6 mm gas layer (Dg-c) at 12.38% (i.e., 3.80 kWh/m^2/year including a cooling reduction of 0.32 kWh/m^2/year and a heating reduction of 3.48 kWh/m^2/year).

The alternative forms of glazing save almost twice as much energy in Beijing's cooler climate than Hong Kong's hotter climate, where the energy savings are less than 10% irrespective of glazing type. For Shanghai's intermediate hot summer/cold winter climate, energy consumption is reduced by 15% at most, with the main trend being around 10%. Double-glazed windows (Group D and Group DT) lead to the most energy reductions in Beijing and Shanghai, while the thermal performance of single-glazing (Group S) is similar in all three cities. As might be expected from the results of previous studies, double low-e window glazing has a better energy performance in all three climates.

5. Discussion

To meet the ambitious emission reduction target, building owners and occupants should be encouraged to adopt suitable retrofit measures to reduce the energy consumption of buildings [21]. Hence, window retrofitting can be an important measure for reducing the energy consumption of buildings in order to achieve the targets. This study evaluated the alternatives window glazing system for a typical high-rise residential building in the three climatic regions in China and demonstrated the potential energy conservation performance.

It has already been mentioned that different climates are likely to generate different energy demands that affect the energy performance of the window glazing types. Table 5 summarizes these effects for the three climates involved in the study. As can be seen, the largest energy reduction for Hong Kong's hot summer/warm winter climate is from low-e glass, although it is less than 10%. In Shanghai's hot summer/cold winter climate, tinted double low-e glazing is best, with savings up to 15%, while clear double low-e glazing reaching around 18% is the most beneficial for Beijing's cold climate. However, depending on the energy reduction target set, these may not necessarily be the most desirable solutions. Table 5 provides some indicative suggestions for the 5%, 10%, and 15% reduction targets based on the savings corresponding to the reduction targets. The findings of this research include a comparison of different window glazing systems, a simulation of the energy saving potentials of different window glazing systems in specific climate zones, and the most suitable window glazing system for different climate zones.

In terms of practical applications, current new residential buildings are still quite similar to the typical existing one used as a base for the model in this study, and therefore these results may help inform the window retrofit design of future such buildings aimed at achieving sustainability targets. However, much further work is needed before this can be done comprehensively. In particular, there is a need to examine the capital costs of window retrofitting. For example, low-e glass is expensive [41], and the price of argon-filled glazing is much higher than that of air-sealed and 6/6 mm double tinted glazing with an air-sealed cavity. Although the 6/13 mm double low-e glazing is the best answer for conserving energy in Beijing, its cost justifies the switching to 6/13 mm double clear conventional window instead. Nonetheless, it is preferable to select the 6/6 mm double grey glazing with air-sealed cavity (Da-g) in Hong Kong. Similarly, advanced glazing systems such as photovoltaic and smart windows may drastically reduce the energy consumption [43,44], but they have many drawbacks such as higher investment cost and uncertain life expectancy [63].

In addition, when applying double-glazing in existing high-rise residential buildings, it is necessary to replace window frames as double- and single-glazing systems require different window frame configurations. Besides, it is time consuming, expensive, and inconvenient to renovate the window frames in an existing high-rise building. Double-glazed windows are also far less energy efficient than 6 mm single grey glazing (Sg) in hot summer/cold winter regions, which may turn out to be the best choice when considering both the cost and operability. On the other hand, window glazing systems have significant impacts on daylight transmittance and comfort. For example, tinted glass windows would reduce the daylight transmittance through the glass, not to mention an improvement in visual privacy. The impacts of different glazing systems on visual transmittance have been explored by Chow et al. [66], and their study discovered that light blue/green tints have higher visible performance and favorable solar heat gain. Similarly, Hee et al. [49] highlighted that switching from clear glass to tinted green glass would reduce space daylighting. For example, about 2.4% higher visual comfort was found when using thermotropic double-glazed windows compared to tinted double-glazed windows [49]. Tinted glass (bronze) with daylight consideration can reduce 14.8% of total energy consumption compared to that without any daylight consideration [44]. Depending on the climatic condition, the findings of this study are supported by previous studies. In the hot summer/warm winter zone (Hong Kong), the highest energy reduction is to adopt low-e glass, while tinted double low-e glazing would serve best (a reduction of 15%) in the hot summer/cold winter climate (Shanghai), and clear double low-e glazing is the most suitable for the cold climate (e.g., 18% for Beijing). In hot climate regions, the use of tinted and low-e glass (double-pane) can reduce 9% and 14%, respectively, of the total annual cooling energy demand (i.e., 7% and 11%, respectively, of the total building energy) compared to that of double-pane clear glass [44]. In temperate climate regions, double-glazed clear panes show higher heating energy saving compared to triple-glazed windows, whereas tinted glass panes can reduce the cooling energy by considerably cutting down on solar transmission compared to clear glass panes in summer. In addition, about 5.1% and 6.4% of the annual cooling energy demand can be saved by single low-e and double low-e glaze windows [85].

Table 5. Energy efficient windows for the three cities.

Possible Energy Efficient Window Retrofitting Measures in Studied Climates													
		Reduction from Traditional Window (%)			**Best Window Choice for Various Requirements**								
					Reduce about 5%			**Reduce about 10%**			**Reduce about 15%**		
Window glazing		Hong Kong	Shanghai	Beijing	Hong Kong	Shanghai	Beijing	Hong Kong	Shanghai	Beijing	Hong Kong	Shanghai	Beijing
6/6 mm single-glazing	Clear (base model)	0	0	0									
	Grey	4.00%	3.13%	−0.89%	****								
	Blue	3.7%	2.92%	−0.82%									
	Clear low-e	3%	5.68%	6.94%		*	**						
	Tinted-low-e	6.48%	8.50%	6.36%				*	*				
6/6 mm double-glazing with air filled	Clear	2.66%	7.30%	11.14%		****				****			
	Grey	6.56%	10.48%	10.41%	***				****				
	blue	6.28%	10.24%	10.46%									
	Clear low-e	5.06%	10.79%	14.23%									**
	Tinted-low-e	7.91%	12.98%	13.68%				**				***	**
6/6 mm double-glazing with argon filled	Clear	2.67%	7.79%	12.38%		***				***			
	Grey	6.69%	11.12%	11.66%	**				***			*	
	blue	6.38%	10.88%	11.71%									
	Clear low-e	5.12%	11.73%	16.52%								**	***
	Tinted-low-e	8.15%	14.19%	16.01%				***				****	***
6/13 mm double-glazing with air filled	Clear	2.66%	8.18%	13.36%		**				**			****
	Grey	6.79%	11.63%	12.65%	*				**				
	blue	6.47%	11.39%	12.71%									
	Clear low-e	5.16%	12.52%	18.40%									****
	Tinted-low-e	8.38%	15.20%	17.94%				****				****	****

(****: best, ***: second best, **: third best, *: fourth best).

Due to higher U-values, windows are associated with the highest energy loss (about 60% in residential buildings). The multi-functional activities of windows, including the passive solar heat gain, ventilation, and lighting, could influence the heating and cooling demands of buildings [86]. Therefore, low U-values and air leakage, as well as suitable SHGC to meet the climatic characteristic should be integrated with the window design to help reduce the energy consumption of buildings. For example, low-e coatings can reduce heat gain through windows by a maximum of 48% [86] but are associated with unaesthetic indoor environment (and may increase the light energy consumption) and higher production costs [87]. In addition, the tinted glazing systems can reduce thermal transmission by more than 20% without compromising other properties such as visible performance [56]. This study also supports that the low U-values of Dgl-t (tinted low-e) and DT-c (clear) with daylight transmittance (in [48] and [85], respectively) are suitable for Beijing and Shanghai, whereas best suitable glazing is Da-g (grey) for Hong Kong (i.e., a lower daylight transmittance due to its higher solar heat gain potential).

Yang et al. [88] showed that the total energy consumption would increase when the WWR is increased, as half of the energy in a building is lost through the window [89]. Thus, it is important to determine the optimal WWR for different building facades to reduce such loss [90]. Overall, the total energy use in office building in different European climates may increase between 5% and 25% when the worst WWR configuration is adopted compared to the optimal WWR [91]. Troup et al. [92] demonstrated that WWR is statistically significant at most of the levels of glazing when predicting the cooling, lighting, and ventilation energy use, but they are not statistically significant for the heating load in office buildings in the US. Marino et al. [93] highlighted that the optimal value of WWR is not strongly influenced by the climate conditions, and also the insulation features of the envelope does not have a strong effect on this parameter, but instead the influence of WWR on the total energy consumption are associated with the operation mode of air conditioning systems, orientation of outside windows, and the glazing types of windows [88].

Future research may cover the impacts of different window frames to include the dividers of the selected window types. Moreover, this study only considers the yearly energy performance improvements when selecting the studied window systems for retrofitting, but the simulation on monthly energy consumption is needed to validate the results and to improve the robustness of this study. While the current study focuses on the energy saving of different window systems, it is imperative to evaluate the payback period of the window type selected in this study with the costs of heating and cooling. Moreover, this study only considers three climatic zones in China, and the study can be extended to other climate zones (e.g., temperate and severe cold regions). While no specific shading system was considered in this study, it can also greatly influence the building energy performance as a shading system would help control daylight transmittance, solar gain, and overheating through windows. For example, shading with integrated micro structural perforated shading screen can reduce the cooling loads by 20%–30% compared to those windows without shading [94]. This study limits its focus to the selection of glazing system in windows, but it is equally important to examine the window installation including the degradation of window insulation and thermal bridge configuration given that the energy performance of windows depends on the type of glazing, frame, and heat transfer coefficients of glazing spacer [95,96]. Apart from selecting the most appropriate glazing system for retrofitting, it is necessary to expand the study to cover different climatic zones. Despite the building envelope, other factors including climate change, ageing, and occupant behavior significantly influences the energy performance of the buildings [97–100], and hence, should be the focus of future research in the studied climatic conditions.

6. Conclusions

China's residential building stock is one the world's largest energy consumers as high-rise residential buildings there take up around 50% of residences in large cities, which is known for its low cost, and construction, with ill-designed windows likely being the major contributors to that. In this paper, we studied the benefits of providing alternative solutions for window glazing systems for a typical high-rise residential block in three different climate zones, namely, hot summer/warm winter; hot summer/cold winter; and cold climates—as represented by Hong Kong, Shanghai, and Beijing, respectively. The design parameters of the case building were fit into a common BIM software Autodesk Revit and energy simulation tool DesignBuilder. The results demonstrated that 6 mm low-e double-glazing with 13 mm air fill serves best in terms of reducing the energy consumption in all the three climatic zones studied, with the highest energy saver being tinted glass for hot summer/warm winter (i.e., 8.38%) and hot summer/cold winter (i.e., 15.20%) climate regions; and clear glass for cold climate (i.e., 18.40%). This type of glazing has advantages in both energy savings and costs, as argon-filled glazing is more expensive than the air filled ones. The relative benefits are greater in cooler climate regions, where the heating load is greater than the cooling load. In addition, the difference between the energy performance of double-glazing filled with air and other types of gas, would gradually increase from almost zero in hot summer/warm winter regions, to a percentage point in hot summer/cold winter regions, and a little more in cold climates; while, the thickness of filled gas has approximately half of the effect. As for existing buildings, many cities are attempting to maximize the prospect of window retrofitting to reach their energy reduction targets. As a result, the work described in this paper and the analytical method used have the potential of informing design teams on how to solve the real-world building window retrofitting problems.

Supplementary Materials: The detailed information of climatic zones and cities are given in the Supplementary Materials, available online at http://www.mdpi.com/2071-1050/11/22/6473/s1.

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