DEVELOPING STANDARD WINDOW TO FLOOR RATIO (WFR) SYSTEM FOR GREEN RESIDENTIAL BUILDINGS IN SUBTROPICS

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ABSTRACT

The window system is generally regarded as the most vulnerable building system for the indoor energy performance of green buildings. Window systems are given significant attention by architects and engineers, especially in areas with long summer and high solar radiation such as the subtropics. This study aims to develop a standard window-to-floor ratio (WFR) system for green residential buildings in the subtropics. Using Autodesk Revit as the interface, a real high-rise residential building was digitalized and imported into Ecotect for energy consumption analysis. Comparative analyses were conducted to determine the optimal WFR for building energy efficiency. Results demonstrated 0.23 as the optimal WFR in Xiamen, one of the typical subtropical cities in Asia. Furthermore, accompanied by a four-sidefins sunshade device and a double glass window (DGW) with clear "glass+air gap+reflective" glass, the building energy consumption was further reduced by 34.47% compared to the initial model, which successfully met the optimization target of 30%, set according to the green building standard. The results of this study are helpful to architects and building engineers when designing or retrofitting green buildings as we provide specific support for design features for energy performance.

KEYWORDS

building energy efficiency, window-to-floor ratio, BIM, Ecotect

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1.0 INTRODUCTION

Amongst all the energy-related elements in a residential building envelope, windows are of major importance allowing direct heat transfer between indoor and outdoor environments, thus the design optimization of window size is a key parameter in reducing the building energy consumption (Salah & Kharvari, 2019). Residential building energy consumption is the second largest sector after the industrial sector globally for energy consumption (Li et al., 2020). In the case of China, building energy consumption accounts for about 27.5% of the total energy consumption, and will gradually increase to more than 30% as the standard of living improves (Wei *et al.*, 2018).

High energy-consuming buildings account for more than 60% of the existing 40 billion square meters of buildings, and most of the 2 billion square meters of newly built buildings per year are still high-energy consuming buildings (Daqi, 2010). New construction area is on average as high as 1.8–2 billion square meters per annum, more than the total construction area in all other developed countries, while the area of new energy-efficient buildings only accounts for about 1% globally (Jun, 2015). Air conditioning accounts for 50%-65% of building energy consumption, 50% of which is lost through doors and windows (Jingmin, 2017). The key factors to change high energy consumption are the design and construction of the building envelope including exterior walls, doors and windows, and roofing (Ávila-Hernández et al., 2020).

Since external wall insulation plays an important role in building energy consumption, many studies have explored the effects of window elements (Teotónio et al., 2020). The window to floor ratio is the ratio of the window opening area of the room to the floor area of the room, referred to as the WFR (Li et al., 2020). The window to wall ratio refers to the ratio of the total area of the external windows in a certain direction to the total area of wall surfaces (including window areas) in the same direction, referred to as WWR. These are commonly used indicators for estimating indoor natural light levels. In 2017, in a case study of the influence of window sizes on building energy consumption under different climatic conditions, a comparative analysis of the optimal WWR of teaching buildings in Saudi Arabia was conducted by Alwetaishi (2019). Chi *et al.* (2020) performed an investigation of the optimal window-to-wall ratio by comparing energy consumption in different building orientations. Through computer simulation, on-site inspection, questionnaire survey, and other research methods, the authors concluded that the orientations with the most significant heat gain are the south and east. The optimal WWR in both hot and dry, hot and humid conditions is 10% (Alwetaishi, 2019). Ghosh and Neogi (2018) summarized the effect of different window sizes and positioning on the heating, cooling and lighting energy consumption of a south-facing building cell in a warm and humid climate. They also compared the energy performance of several external shading devices to put forward a new design of sunshade device. Hee *et al.* (2015) summarized previous research on the impacts of window glazing on the energy, the performance of glazing options, and of building and optimization techniques for choosing glazing. Many studies have explored the effects of WWR on energy consumption; however, the common limitation is that they failed to specifically propose a recommended window size suitable for specific areas and building standards, or they simply claim it is challenging to achieve desired outcomes in actual applications and provide no guidance on how to achieve the outcomes (Li et al., 2020; Ávila-Hernández et al., 2020; Teotónio et al., 2020).

Developing window performance in building energy saving has become a hot topic, and one of the foremost has been smart window technology. Ke *et al.* (2018) systematically summarized merging thermoresponsive materials for smart window applications, including hydrogels, ionic liquids, perovskites, metamaterials, and liquid crystals. Wei *et al.* (2010) evaluated 13 essential design parameters of the dual-airflow window for energy-saving and found that the dual-airflow window could save 25% energy in a warm climate region such as Guangzhou and 34% in a cold climate region such as Harbin. Thermochromic(TC) windows were recognized as a passive building component to improve indoor comfort and building energy saving in place of traditional clear glazing systems. Liang *et al.* (2018) explored the potential of TC glazing under various climatic conditions in a typical office and found that all studied TC windows had superior performance in building energy conservation, especially in hot regions. From the perspective of energy saving in windows, there are many studies on window performances, but most of them involved new materials, new structures, and new designs. Although these new designs have advantages in building energy conservation, from the economic and construction point of view, it is expensive, unpractical, and challenging to promote widely. Therefore, this study chose the WFR as the research object. Although slightly inferior in terms of energy consumption reduction, it has advantages in terms of cost and construction compared with other energy-saving measures.

This study proposed a solution for efficiently calculating the WFR under the standard of green building. Our method was based on the summary of architectural design regulations domestic and abroad. We then generated a reasonable object of energy consumption saving for the design of green WFR. Many studies showed that the utilization of daylight through elaborate design and operation of windows leads to significant energy savings in both cooling and lighting. Because of the climatic diversity in China, the designs of windows and the analysis on window thermal performance could vary greatly. However, the latest studies have not considered the specific design requirements for a window in a specific area with different climates. Considering those obstacles, this study aims to develop a feasible approach for designing green WFR with known building information models and climate information in Xiamen. The methodology proposed includes changing the window sizes as well as optimizing the glass structure, adding shading systems and other facilities to reduce the direct sunlight, and optimizing the building energy consumption to the required object. The calculation method of green building WFR used by this study is not limited to residential buildings but provides a reference method for the window element design of various residential buildings in hot summer and cold winter areas in China.

2.0 RECENT DEVELOPMENT ON OPERATING PERFORMANCES OF GREEN BUILDINGS

2.1 Green building standard and WFR in China

Buildings, energy, and the environment are key issues that architects and energy policymakers have to address (Yang *et al.*, 2008). China faces unprecedented energy constraints that other developed countries haven't faced in the process of their economic development and urbanization. In 2006, China pledged to reduce its carbon intensity by 40–45% by 2020. Furthermore, the Chinese government has also planned to decrease energy intensity by 16% during the 13th five-year plan period. 'The Design Standard For Energy Efficiency Of Public Buildings' GB 50189-2015 (MoHURD, 2015) is a national standard developed by the Ministry of Housing and Urban-Rural Development of the People's Republic of China. This standard is formulated for the implementation of relevant national laws, regulations, guidelines, and policies, improving the indoor environment of public buildings, improving energy efficiency, promoting the application of renewable energy, and reducing building energy consumption. The standard adopts the five climate zones defined in another national standard GB 50176-93 (NTSB, 1993): 'Thermal Design Code for Civil Buildings' organized by the National Technical Supervision Bureau and Ministry of Construction. The five climates are respectively the Severe Cold Region, Cold Region, Hot-Summer Cold-Winter Region, and Mild Region. There are different residential energy-saving design standards according to different climate regions. Taking Xiamen city as an example, this city experiences hot summers and warm winters, so the designer should turn to the 'Energy-saving Design Standards for Residential Buildings in Hot-Summer and -Warm-Winter areas' JGJ-2012 (MoHURD, 2012). The mandatory requirements for standard cover window are detailed as follows:

Building design and thermal energy-saving: the ratio of the single window-to-wall area should not exceed 0.40 in the south and north directions; the window-to-wall ratio in the east and west directions should not exceed 0.30. The window-to-floor ratio of the buildings' rooms (e.g., bedroom, study, and living rooms) should not be less than 1/7. When the window-to-wall ratio is less than 1/5, the visible light transmittance of the outer window glass should not be less than 0.40. In the 1960s, American architect Paul Soller proposed the then new concept of ecological architecture. In 1980, the World Conservation Organization first proposed the slogan of 'sustainable development;' at the same time, the energy-efficient building system was gradually improved and widely used in developed countries such as Germany, Britain, France, and Canada. Another important regulation is the 'Assessment Standard For Green Building' GB/T 50378-2019 (MoHURD, 2014). The 'Assessment Standard For Green Building' has undergone two revisions since its first publication in 2006. The latest revision called 'Assessment Standard For Green Building' GB/T 50378-2019 was officially launched on August 1, 2019. The new regulation revised the definition of green building and paid more attention to high quality. Green buildings are defined as those high-quality buildings that save resources, protect the environment, reduce pollution, provide people with healthy, suitable and efficient use spaces, and maximize the harmonious coexistence of man and nature. Different evaluation indicators are scored, and the grade of green building is determined by the total score on the premise that each type of evaluation index scores meets the minimum score requirement in the regulations. The total score for the reasonable selection and optimization of heating, ventilation and air conditioning systems is 10 points, and different score intervals are as shown in Table 1 and Table 2. The margin of reduced energy consumption in heating, ventilation and air conditioning system (De) needs to be more than 5% to meet the requirements of green building standards (in Table 3).

The 2019 version uses the cumulative addition method of absolute scores for calculation, and a new basic score item is added. The full score of this item is 400 points. As long as all are met, the full 400 points can be attained. The seven scoring items are accumulated and averaged, which is the total score of green building evaluation.

In order to promote the implementation of the national standards, many provinces have successively proposed green building evaluation standards based on the province's climatic conditions and the level of economic development. Tables 4 and 5 show the relevant requirements in the 'Fujian Green Building Evaluation Standard' DBJ/T13-118-2014 (FPDoHURD, 2014).

WWR and WFR can both be used for evaluating the indoor natural light levels. When formulating local standards, these can be selected according to local conditions. In areas with hot summer and warm winters, the use of WWR has encountered some problems in actual use without restrictions on the shape of windows. For buildings with large external walls, even

TABLE 1. Evaluation index scores of the new standard.

	Basic score of control items	Full score for each item					Bonus for improvement and innovation
		Safe and durable	Health and comfort	Convenience	Resource saving	Environment-friendly	
Score of pre-evaluation	400	100	100	70	200	100	100
Score of evaluation	400	100	100	100	200	100	100

TABLE 2. Specific description of the score item of the envelope structure is 5%.

Reduction ratio of enclosure structure thermal performance	Score	Reduction ratio of heating and aire conditioning load	Score
5%	5	5%	5
10%	10	10%	10
15%	15	15%	15

TABLE 3. Score of different margin intervals of reduced energy consumption in heating, ventilation, and air conditioning system.

The Margin (De)	Score
5% ≤ De < 10%	3
10% ≤ De < 15%	7
De ≥ 15%	10

TABLE 4. Building energy consumption analysis comparison.

The requirements of Window-to-Floor ratio	> one-seventh in bedrooms
The requirements of energy saving	≥ 30%

TABLE 5. Limits of window-to-wall ratio in different directions.

Direction	South	North	East	West
Maximum	0.4	0.4	0.3	0.3

if the windows are large, the shading coefficient of the windows will be less strict. This means that for some buildings with a particularly large shape factor, when the same shading factor is adopted, a larger area of the outer window will be allowed. This result is unreasonable.

Therefore, the WFR was used in this study for evaluating the light level of each room. It also made the building energy-saving design and building natural lighting design consistent with the building natural ventilation design.

2.2 Optimization object of energy saving

The 'Building Energy Efficiency Design Standards for Summer and Warm Winter Zones'JGJ 75-2012 (MoHURD, 2012) requires total energy consumption savings of 50%. The three-step goal of building energy efficiency proposed by the state is: firstly, saving more than 30% energy consumption than the 1980s; the second step requires 50% energy saving, and the third step is to reduce energy consumption by 65%. At present, Beijing, Tianjin, and some other places have taken the lead in implementing 65% energy-saving design standards. This means that in the next few years, the step of 65% energy saving will inevitably be popularized. Therefore, this study is aimed at a 65% reduction in consumption to make a meaningful reference. We will only optimize the energy consumption of the window but not the energy-saving design of the whole building.

The energy consumption of the envelope structure accounts for about 85% of the energy consumption of the entire building (Tao, 2012), while the energy consumption of the heating, ventilation and air conditioning systems account for about 55% of the energy consumption of the building envelope (Daqi, 2010). Therefore, the objective for required energy reduction percentage is: $65\% \times 85\% \times 55\% \approx 30\%$, when the final optimized building model energy consumption is reduced by more than 30% compared with the original model, achieving the purpose of the study.

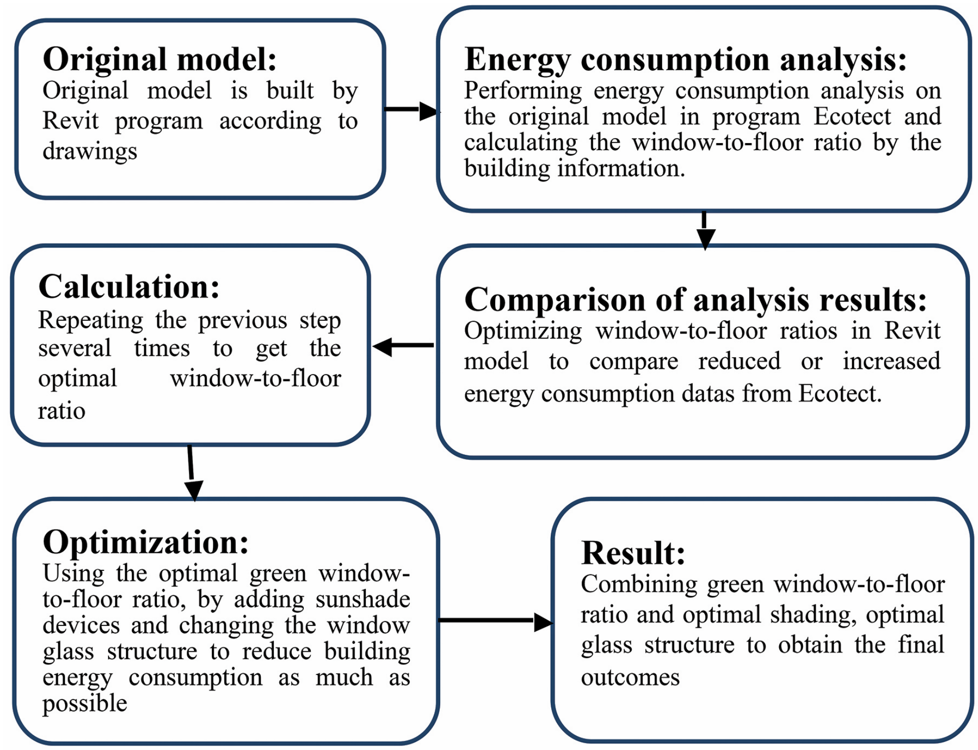
3.0 RESEARCH METHODS AND PROCEDURES

The methodology for developing green WFR in this study included three main procedures. In the first step, an extensive literature review on the study of window performance in building energy and related norms on building window design was conducted. The main norms came from the national standard of the People's Republic of China and local regulations. Specifically, Building Information Model (BIM) and energy analysis software Ecotect were reviewed first to help understand the relationship between window area and building energy consumption.

In the second step, the simulation began based on the high-rise residential building model built by Revit. The simulation framework to explain the process of the simulation is presented in Figure 1. The initial model contained accurate building materials, building structure, space volume, and other necessary building information. It is worth noting that the model was simplified by removing railing balcony components that had no effect on the analysis after the model file was imported into Ecotect. Second, the change of WFR was reflected in the change of the size of windows in the Revit model after the model was built and simulation analysis, using Ecotect, was undertaken to obtain the specific energy consumption information of the building. In addition, we used Revit to modify the model and use Ecotect again to analyze. Finally, the desired Green WFR was obtained from the optimal energy consumption results.

Finally, in order to enhance the energy-saving effect of windows, other factors that affect the energy consumption of buildings, such as the external sunshade and the kind of glass were adopted.

FIGURE 1. The framework of research.



3.1 Research tools employed

This study used BIM software to establish a model, containing building material information and detailed information about windows. As a revolutionary technology and process, BIM provided an effective platform to overcome data acquisition issues, providing great potential for life cycle assessment of the entire building during the design phase (Eastman *et al.*, 2011). As BIM and green building both continuously gain momentum, growing architecture, engineering, and construction (AEC) firms are embarking on green BIM practices (Wong and Kuan, 2014). BIM could facilitate data exchange and integration, provide visualized building performance analysis and enhance the communication and collaboration of various stakeholders during the life cycle of green building. Lu *et al.* (2017) summarized seven major BIM functions for environmental sustainability analysis, including energy performance analysis and evaluations, carbon emission analysis, natural ventilation system analysis, solar radiation and lighting analysis, water usage analysis, acoustics analysis and thermal comfort analysis.

Autodesk Revit is BIM-based software that professional design and construction personnel use for a coordinated, model-based approach to transform design ideas from the original concept into a feasible building. It is also a comprehensive application that includes features for architectural design, water, heating, electrical and structural engineering, and engineering construction. Autodesk Ecotect Analysis is an energy simulation tool that is compatible with BIM software such as Autodesk Revit Architecture and allows a comprehensive preliminary building energy performance analysis. Ecotect software is an environmental analysis tool that allows designers to simulate building performance in the conceptual phase. It provides thermal, lighting and acoustic analysis, including hourly thermal comfort, monthly space loading, natural and artificial lighting levels, acoustic reflection, reverberation time, project cost and environmental impact (Crawley *et al.*, 2008). Various studies have shown that Ecotect simulations are highly accurate (Aldali and Moustafa, 2016; Anand *et al.*, 2017; Omar *et al.*, 2018). Studies have used Ecotect and BIM models to calculate the life cycle energy consumption and carbon dioxide emissions of a building and results show that it is a powerful software tool for simulation analysis (Basbagill, 2013).

3.2 Xiamen climate conditions

Xiamen city is located 118 degrees 08 minutes east longitude and 24 degrees 28 minutes north latitude. It is in the southern part of Fujian Province. Xiamen has a subtropical maritime monsoon climate. The main climatic characteristics are mild and rainy, not too cold in winter but hot in summer (see Figure 2). The annual average temperature is around 21 degrees Celsius. The average annual wind speed is 3.4m per second. Xiamen's annual temperature and rainfall can be divided into 5 distinctive seasons: in the spring rain season (March to April) rainfall is about 100 mm, in the rainy season (May to June) rainfall is about 350 mm, in the typhoon season (July to September) rainfall is about 200 mm, in the autumn (October and November) the average rainfall is about 80 mm, and in the winter (December to February) the average rainfall is about 146 mm. The interannual variation of sunshine hours in Xiamen (Figure 3), shows a four-category area with annual sunshine hours ranging from 1,400h to 2,200h, indicating that it is a sunshine rich region.

The WFR used in this study was more convenient than other general approaches for optimizing window designs. Notably, in hot summer and warm winter areas like Xiamen, the summer period is long and solar radiation is significant, meaning the energy loss of buildings through

FIGURE 2. Map of China according to the climate region (Xiamen (118°04′ E, 24°26′ N) is marked by a star).

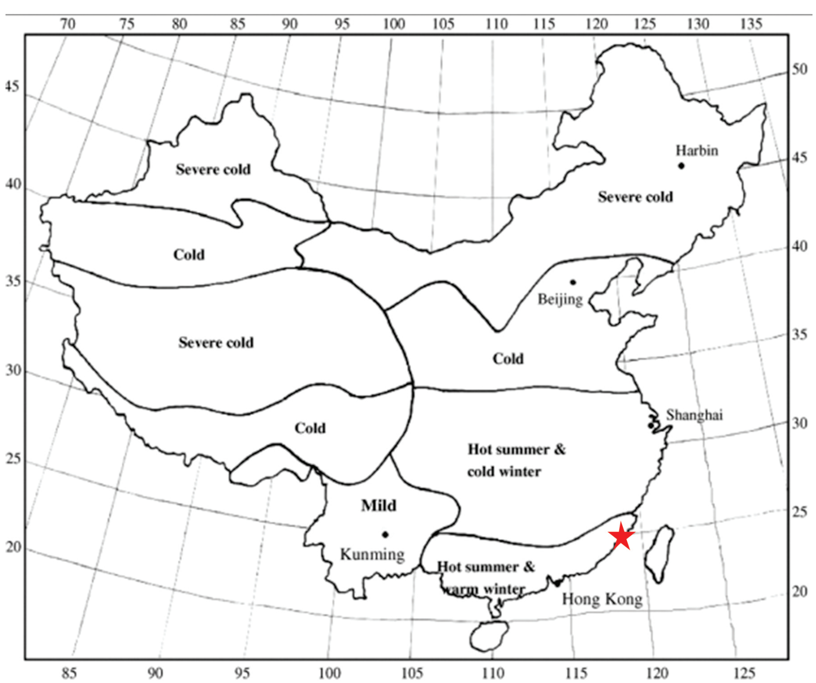
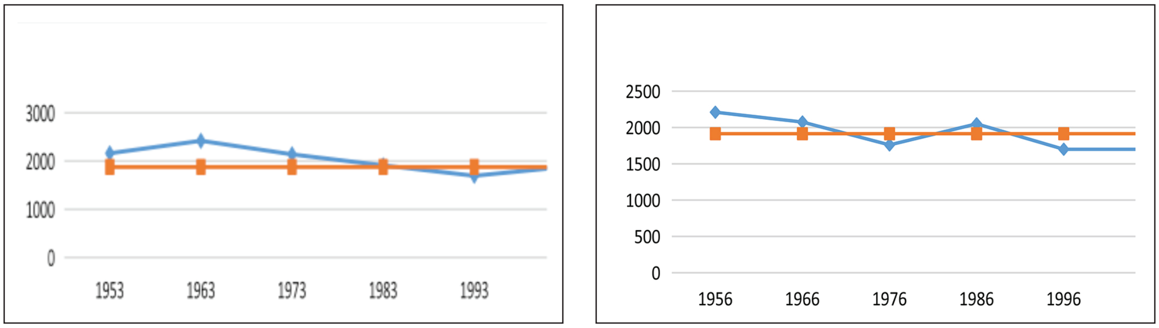


FIGURE 3. Interannual variation of sunshine hours in Xiamen (a. inside the island; b. off the island; Data source from Xiamen City Meteorological Bureau official website: http://fj.cma.gov.cn/xmsqxj/).



(a) (b)

the window system is even greater, and, therefore, it is important to save building energy consumption by studying the WFR.

3.3 Model development

A virtual high-rise residential building was created as a simulation model. Figue 4 shows the model profile (left) and standard floor plan (right) of the analyzed building in the simulation software. The building is located in Xiamen, Fujian Province. There are ten floors, and each floor is 3m high. The building has a total elevation of 34.2m, which is standard for a high-rise residence. The building has a cast-in-place reinforced concrete frame-shear wall structure. The total area of this building is 5,800 square meters. On a typical floor, every household has bedrooms, a living room, a kitchen, a dining room, and bathrooms. The dimensions of the original windows can be seen in Table 6.

FIGURE 4. The model profile (left) and standard floor plan (right).

TABLE 6. The sizes of windows in the initial model.

	Area of windows m^2	Area of the floor m^2	Window-to-floor ratio	Orientation	Size
Master room 1	2.7	22.68	0.12	South	1500×1800
Guest room 1	1.8	16.38	0.11	South	1200×1500
Dinning room 1	4.2	44.55	0.10	South	2000×2100
Kitchen 1	1.8	7.26	0.25	West	1200×1500
Large bathroom 1	0.9	6.60	0.14	North	600×1500
Bathroom 1	0.9	2.40	0.38	West	600×1500
Bedroom 1	2.25	13.86	0.16	North	1500×1500
Master room 2	2.7	22.68	0.12	South	1500×1800
Guest room 2	1.8	16.38	0.11	South	1200×1500
Dinning room 2	4.2	44.55	0.10	South	2000×2100
Kitchen 2	1.8	7.26	0.25	North	1200×1500
Large bathroom 2	0.9	6.60	0.14	North	600×1500
Bathroom 2	0.9	2.40	0.38	West	600×1500
Bedroom 2	2.25	13.86	0.16	North	1500×1500
Master room3	2.7	22.68	0.12	North	1500×1800
Guest room 3	1.8	16.38	0.11	North	1200×1500
Dinning room 3	4.2	44.55	0.10	North	2000×2100
Kitchen 3	1.8	7.26	0.25	South	1200×1500
Large bathroom 3	0.9	6.60	0.14	East	600×1500
Bathroom 3	0.9	2.40	0.38	South	600×1500
Bedroom 3	2.25	13.86	0.16	South	1500×1500
Master room4	2.7	22.68	0.12	North	1500×1800
Guest room 4	1.8	16.38	0.11	North	1200×1500
Dinning room 4	4.2	44.55	0.10	North	2000×2100
Kitchen 4	1.8	7.26	0.25	South	1200×1500
Large bathroom 4	0.9	6.60	0.14	East	600×1500
Bathroom 4	0.9	2.40	0.38	South	600×1500
Bedroom 4	2.25	13.86	0.16	South	1500×1500

Basic simulation conditions. The purpose of modelling with Revit was to enable an analysis of the building information. The building information contained in the model built by Revit was more abundant than the building information directly modelled by Ecotect. For example, Revit could directly generate information such as tables of door and window data and various surface and material information. For this reason, Revit was chosen to build the information model. The transfer process could be summarized as exporting the model in Revit to an FBX format file in 3D view format, then opening it in 3Dmax, exporting the file to 3D format with 3Dmax, and finally opening the file in a 3D format in Ecotect. The distribution of materials in the model was simplified in Ecotect. The specific structural properties of each component after simplification are shown in Table 7. Since the study was mainly for windows, the most basic construction practices for the walls, roof, and floor materials were constructed and remain unchanged throughout the study.

Area properties settings. The system type, number of people, heat generation of the equipment, and activity/run schedule were set before the simulation. Since the energy consumption analysis in Ecotect was based on the volume of the area, the structure of the high-rise residential building in this study was the same for each floor. To shorten the calculation time, the main function rooms were divided into bedroom class area, leisure entertainment area, auxiliary class area classification, and the area attribute settings were respectively set.

Main settings: The 'General Settings' tab was used to set the running time of the air conditioning. The specific running time was divided between workdays and weekends, each with different start and close times. The 'Thermal Environmental Attributes' tab was used to set the regional environment parameters to a hot climate. The settable contents included system type, personnel equipment, penetration, and operation schedule. Since it was a high-rise building with a full air conditioning system, the air conditioning system was set as a "full air conditioning system."

The 'Area volume and area adjacent' analysis provided an inner region adjacent calculation that was primarily used to detect the spatial geometric relationship between the regions. In general, Ecotect automatically calculated the volume within the area and the internal area adjacent before performing the correlation analysis. To ensure that the analysis was correct, one could manually perform intra-area volume calculations and regional neighbour commands again. The setting requirements for each area are in Table 8:

Loading weather data

Ecotect calculations were based on local meteorological data conditions (Xiamen City Meteorological Bureau official website: http://fj.cma.gov.cn/xmsqxj/) of the model, thus this needed to be loaded beforehand. The specific data setting steps were as follows in Figure 5: 1) select "Model Settings "Button in the main toolbar, 2) enter the Data/Time/Location tab in the Model Setting dialog box, 3) click the "Load Climate Data" button, 4) load "Climate conditions in Xiamen, China," and 5) confirm that the meteorological data content matches the model longitude and latitude.

4.0 RESULTS AND FINDINGS

4.1 Analysis on original model

Analysis on hourly temperature curve. Energy analysis was conducted in the program Ecotect (Autodesk® Ecotect® Analysis 2010). Figure 6 shows the hourly temperature curves for all areas

TABLE 7. The simplified settings of material in the envelope structure.

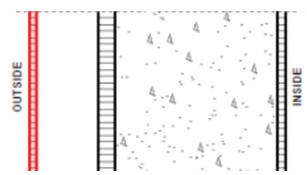
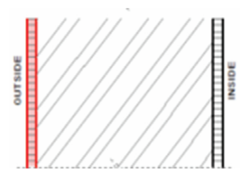
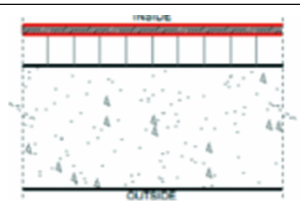
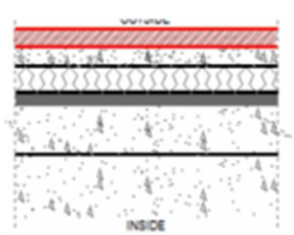
	Structure details		Specific tectonic of each layer properties					
			Name	Width (mm)	Density (kg/m^3)	Specific heat (J/kg·K)	Thermal conductivity (W/m·K)	Type number
Exterior wall		1	Plaster building	10.0	1250.0	1088.000	0.431	85
		2	Plaster building	20.0	1250.0	1088.000	0.431	85
		3	Concrete cinder	200.0	1600.0	656.900	0.335	35
		4	Plaster building	10.0	1250.0	1088.000	0.431	85
Interior wall		1	Plaster building	10.0	1250.0	1088.000	0.431	85
		2	Brick masonry medium	180.0	2000.0	836.800	0.711	25
		3	Plaster building	10.0	1250.0	1088.000	0.431	85
Floor		1	Concrete	120.0	3800.0	656.900	0.753	35
		2	Solid	30.0	2500.0	840.000	1.050	75
		3	Brick	10.0	1920.0	840.000	0.720	25
Roof		1	Ceramic tile	30.0	2435.0	656.900	1.590	21
		2	Cement/lime plaster	30.0	1600.0	840.000	0.800	35
		3	Cellulose triacetate	1.0 (thickness ignored)	1300.0	1464.000	0.251	95
		4	Polystyrene preformed propose	40.0	40.0	1130.000	0.042	45
		5	Plaster board	20.0	1250.0	1088.000	0.431	85
		6	Concrete stone	80.0	2300.0	656.900	1.046	35
		7	Concrete lightweight	100.0	950.0	656.900	0.209	35

TABLE 8. The attributes of main areas.

Regional Area	General tab properties	Thermal environment properties	The room information
Leisure area: Living room dining room	**Interior design conditions:** Clothing quantity: v1.00 clo Humidity: 60.0% Wind speed: 0.50 m/s Illuminance: 400 lux **Personnel and operation:** Number: 6 Activity intensity: cooking 95w	**Active system:** Type: full air conditioning system Effectiveness: 95.0% **Temperature control range:** Lower limit: 18.0°C Upper limit: 26.0°C **Operation hours:** Normal: 17–22 Weekend: 15–22	**Area:** 1st floor living room dining room 1 **Total area:** 205.080 m^2 **Floor area:** 45.240 m^2 **Volume:** 137.217 m^3 **Status:** No adjacent
Bedroom	**Interior design conditions:** Clothing quantity: 0.40 clo Humidity: 60.0% Wind speed: 1.00 m/s Illuminance: 300 lux **Personnel and operation:** Number: 2 Activity intensity: rest 45w **Indoor heat:** Sensible heat: 5 w/m^2 Gain heat: 2 w/m^2	**Active system:** Type: full air conditioning system Effectiveness: 95.0% **Temperature control range:** Lower limit: 18.0°C Upper limit: 26.0°C **Operation hours:** Normal: 22–8 Weekend: 20–10	**Area:** 1st floor the master room1 **Total area:** 105.660 m^2 **Floor area:** 22.680 m^2 **Volume:** 68.040 m^3 **Status:** No adjacent
Bathroom	**Interior design conditions:** Clothing quantity: 0.60 clo Humidity: 60.0% Wind speed: 0.50 m/s Illuminance: 200 lux **Personnel and operation:** Number: 3 Activity intensity: cleaning 45w Indoor heat: Sensible heat: 5 w/m^2 Gain heat: 2 w/m^2	**Active system:** Type: none Effectiveness: none **Temperature control range:** Lower limit: 18.0°C Upper limit: 26.0°C **Operation hours:** Normal: 0–24 Weekend: 0–24	**Area:** 1st floor bathroom 1 **Total area:** 45.000 m^2 **Floor area:** 6.600 m^2 **Volume:** 19.844 m^3 **Status:** No adjacent

FIGURE 5. Interface for loading the weather data.

of the model on 3rd July, which was the day with the strongest sunlight in Xiamen. The blue dotted line indicated the outdoor temperature, the yellow broken line indicated direct sunlight, and the yellow dotted line indicated solar scattering. The green broken line indicated wind speed, the thick solid line indicated the different areas, and the double solid line indicated the selected area. Figure 6 indicates that the outdoor temperature was basically above 25 degrees Celsius, and the temperature in the afternoon was more than 30 degrees Celsius from 13:00 to 15:00. In a room with air conditioning, the temperature was maintained around 26 degrees Celsius, and when the air conditioner was not running, the temperature was the same as the outdoor temperature. When the wind speed began to slow down after 12 o'clock, the temperature reached the highest point of the day.

Analysis on hourly heat loss and gain. The hourly heat gain/loss analysis contained data associated with building energy consumption for every hour in a day. In the hourly heat analysis chart, the hourly heating and air conditioning load, the heat gain or loss by the thermal conductivity of the envelope structure, the heat generated by the integrated temperature, the heat coming from direct sunlight radiation, the impact on heat from cold air penetration, and the heat gain or loss from internal personnel along with equipment were included.

FIGURE 6. Hourly temperature curves.

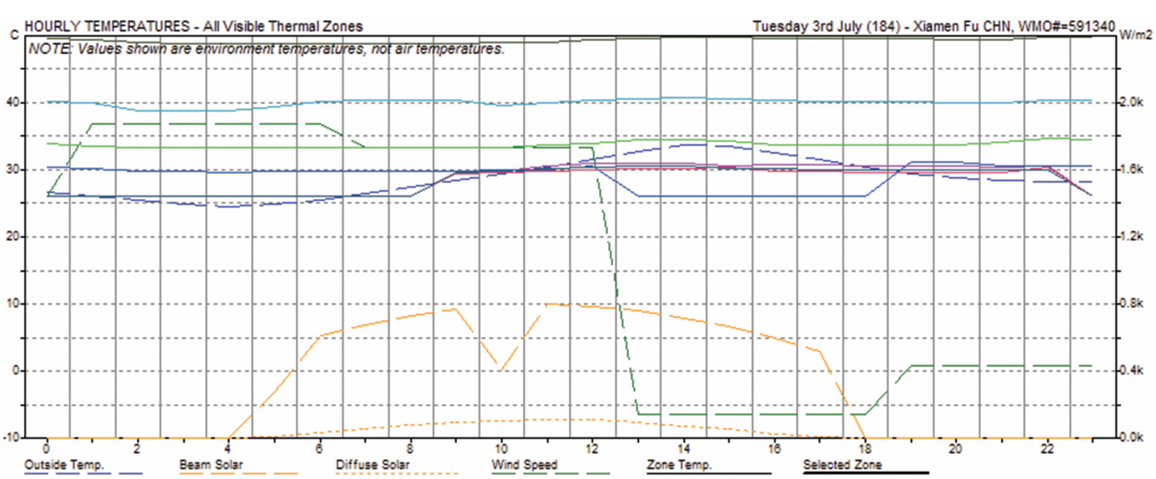


Figure 7 shows the effects of the hourly heat source during the hottest day of the year in Xiamen, as well as the energy consumption of the air conditioners. The solid green line indicated the load of heating, ventilation and air conditioning (HVAC). The solid red line indicated the thermal conductivity of the envelope structure. The dotted red and yellow line respectively indicated the heat generated by the integrated temperature and direct sunlight radiation. The solid green line indicated the heat gain or loss by cold air penetrations. The solid purple line indicated the variation of the heat gain or loss by internal personnel and equipment. The solid blue line shows the heat gain or loss between regions. When the temperature was above 0°C, it meant gaining heat, below meant losing heat. The highest energy consumption in Xiamen within one day was the HVAC load. In contrast, the most heat loss in the indoor area was the heat loss between the regions. The heat loss between the regions referred to the heat at the junction of different regions; when heat loss was a concern, more attention should be paid to the airtightness of the building. Poor connectivity led to loss of heat. The changing trend of inter-area heat loss and air-conditioning energy consumption was similar. In summary: a) the energy consumption was driven by air conditioning, and it was higher than other sources of energy consumption. The importance of air conditioning was due to the climatic characteristics of Xiamen, where air conditioning was often kept running for much of the day; b) the only way to lose heat was through inter-zone transfer. In summer, the radiant heat of the glass window formed part of the summer cooling load, which was beneficial. As heat loss increased, HVAC loads reduced; and c) the outdoor temperature played a decisive role in building energy consumption and heat conduction inside the building.

Analysis on monthly degree days. The analysis of monthly degree days consisted of two parts as in Figure 8. On the left, horizontal coordination represents the month while the vertical coordination represents the degree day (DD). The degree days were classified into cooling degree days (CDD) and heating degree days (HDD). The CDD was the value of days when the outdoor average temperature was higher than 26°C, multiplied by the corresponding temperature differences. The HDD denoted the value of days when the outdoor average temperature was below 18°C multiplied by the corresponding temperature differences. The units of both CDD and HDD were °C. On the right, horizontal coordination represented the energy gain, and

FIGURE 7. Hourly heat loss and gain curve.

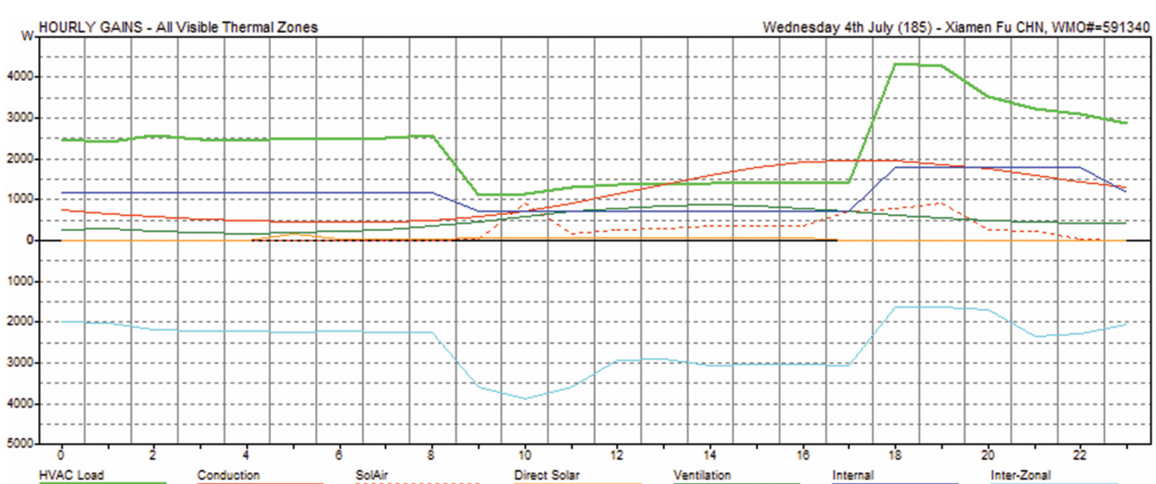
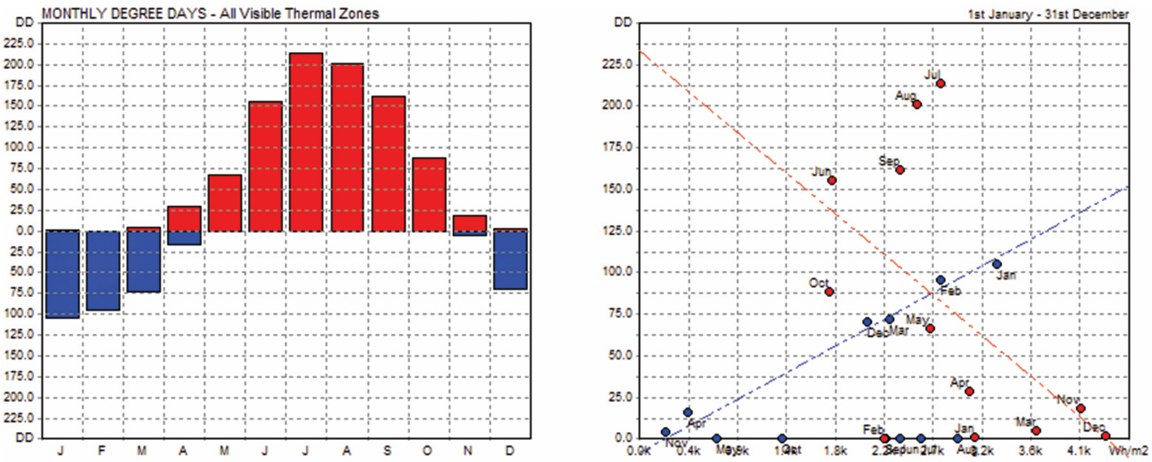


FIGURE 8. Analysis of monthly number of days, histogram (left) and scatter plot (right).



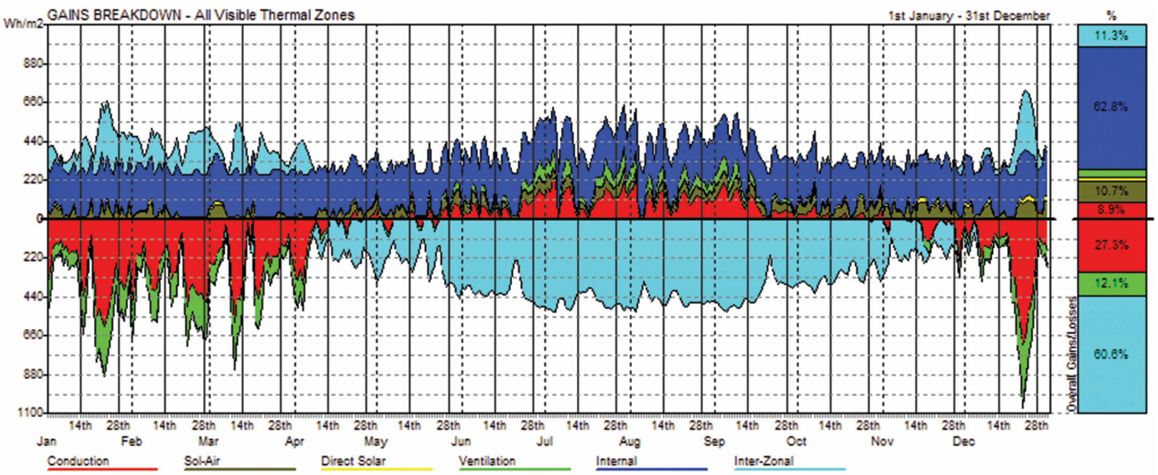
vertical coordination represented the degree days (DD). Figure 8 indicated that the annual heat gains of the building far exceeded that of heat loss, except for the January, February, March and December. The maximum number of heat loss days was only about 100dd. In summary: a) the amount of building heat in Xiamen was several times that of heat loss, and heat energy dominated among eight months of the year, and b) to reduce the energy consumption of buildings in Xiamen, the energy consumption was to be reduced in summer, especially the air conditioning energy consumption.

Building energy efficiency strategies were generally divided into active and passive. The active energy-saving strategy referred to reducing the consumption of non-renewable resources through the use of renewable resources, such as the use of solar energy. Conversely, the passive way to reduce energy consumption referred to building energy-saving design changes (such as the building orientation, window-to-wall ratio, natural ventilation and lighting, and thermal insulation materials), rather than relying on fossil fuels or other mechanical power equipment.

Using Ecotect to perform the passive component, thermal analysis identified the primary source of heat gain. Figure 9 shows the daily variation of heat from different sources within a specified date range and their respective proportions. The lines in the picture show the heat gain in terms of inter-zone, internal equipment, ventilation, direct solar radiation, comprehensive so-air, and the envelope. The specific data ranged from the 14th to 28th of each month. There was 82.8% heat gain generated by indoor heat, which was mostly determined by the outdoor temperature, while less than 20% of the heat gain came from air, solar light, and ventilation. Thus, reducing summer heat was critical to building energy sufficiency. The heat was evenly distributed, from January to December, indoor heat gains accounted for most of the heat. The peak reached in July, August, and September, and the rest of the time dropped slightly.

Analysis of monthly energy consumption. Through monthly energy consumption analysis in the following charts, the monthly energy consumption ratio of each region over the year were obtained. The horizontal coordination in Figure10 was the month, and the vertical coordination was energy consumption. The portion below the 0 scale line in the column chart indicated the amount of cooling energy consumption, and the portion above the 0 scale line indicated

FIGURE 9. Analysis of passive heating component.

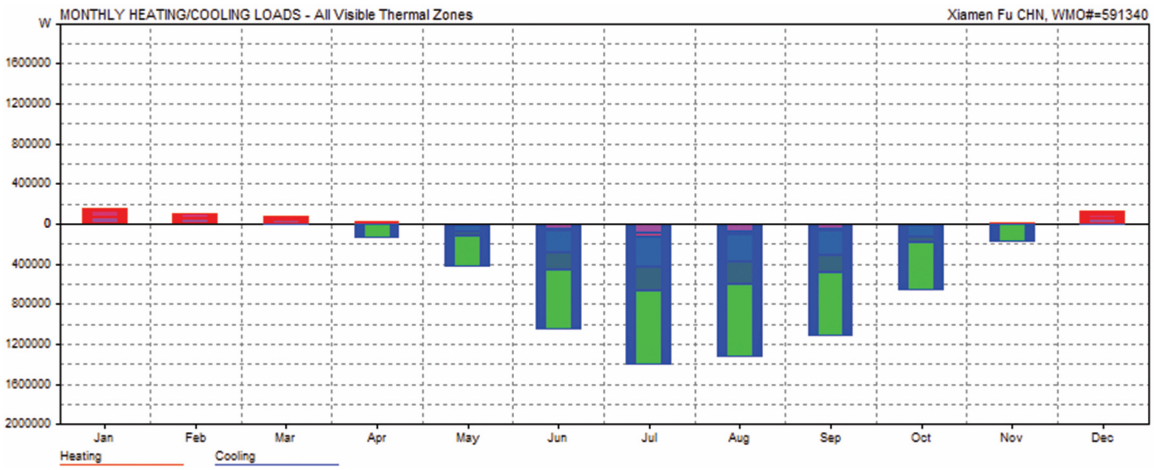


the amount of heating energy consumption. The annual cooling energy consumption was considerably higher than the winter heating energy consumption. Table 9 shows the specific energy consumption data statistics in Figure.10. The total energy consumption of cooling energy consumption was 8,853,151wh, which was 13.2 times the heating energy consumption of 500,772wh. The annual cooling energy consumption accounted for 93% of the total energy consumption of the building. The highest cooling energy consumption came in July, the highest

TABLE 9. Analysis on original monthly energy consumption.

Month	Heating (wh)	Cooling (wh)	Sum (wh)
Jan	150835	0	150835
Feb	91611	0	91611
Mar	69813	13468	83281
Apr	23603	211582	235185
May	0	617304	617304
June	0	1474560	1474560
July	0	1940658	1940658
Aug	0	1838304	1838304
Sep	0	1554162	1554162
Oct	0	963302	963302
Nov	19254	239811	259065
Dec	145656	0	145656
Total	500772	8853151	9353923

FIGURE 10. Analysis of monthly heating/cooling loads.



cooling energy consumption was 1,940,658wh, the highest heating energy consumption came in January, and the highest heating energy consumption was 150,835wh.

4.2 Green WFR calculation approach

Sizes of windows in the original model. After the initial model was completed, the energy consumption was analyzed using the software Ecotect. The thermal environment and energy consumption of the original model were analyzed from the perspectives of energy consumption, temperature, and heat loss. The sizes of the windows were then optimized to reduce the energy consumption of the model. When optimizing the WFR, the energy consumption result analysis was used including monthly energy consumption analysis and monthly number of days analysis.

The WFR optimization of this study started from 1/7 (equivalent to about 0.15), and the maximum window-to-wall ratio of the building was specified in the 'Green Building Evaluation Standard of Fujian Province' DBJ/T13-118-2014 (FPDoHURD, 2014). Considering that the maximum window-to-wall ratio and the area of the building envelope were restricted, the maximum WFR was considered at 0.24. The optimal WFR was kept in the range of 0.15~0.24, which minimized the building energy consumption.

The specific method for optimizing the WFR was to compare the energy consumption analysis result of the optimized model with the result before optimization, and if the current energy consumption was reduced compared with the one before optimization, the result was retained; otherwise, the adjustment of the windows continued.

Selection of window shape and façade. Considering the preferred shape and orientation recommended by De Luca and Voll (2016), the model in this research was selected to be oriented in the direction of the south and the north and the windows were horizontally shaped and located in the south and north.

Analysis on each optimization of WFR. The first WFR optimization used the minimum WFR required by the specification of 0.15. The overall energy consumption is shown in Table 10 and

Table 11. The total energy consumption of the building dropped from the original 9,523,573wh to the first optimized 9,280,886wh, a decrease of 2.55%, in both heating and cooling energy. As the total energy consumption of the building was reduced, optimization continued.

In the process of optimization, it was found that increasing the WFR led to an increase in winter heating, but a decrease in summer cooling. Since the summer cooling load accounted for the majority of the total load, the total load still showed a downward trend and the proportion of decline increased. However, as the window ratio increased by more than 0.19, the rate of decline began to slow down. The rate of increase in heat loss remained unchanged, but the rate of increase in heat declined. When the WFR increased from 0.23 to 0.24, the total energy consumption increased.

In summary, for the high-rise residential buildings in this study, values beginning from one-seventh of the requirements (e.g., take 0.15) could be used. The seven times optimization values were 0.15, 0.17, 0.19, 0.22, 0.23, and 0.24, respectively. Based on the seven times' optimization, the models were built separately and analyzed monthly. The preferred WFR in Xiamen high-rise residential buildings was determined to be 0.23.

TABLE 10. Statistical table of seven times optimized annual total energy consumption.

Window-to-floor	origin	0.15	0.17	0.19	0.21	0.22	0.23	0.24
Annual total energy consumption (wh)	9353923	9115613	8631131	8404375	8381399	8366996	8323583	10901851

TABLE 11. Statistical table of energy consumption per month for seven times optimization.

	monthly energy consumption							
	origin	0.15	0.17	0.19	0.21	0.22	0.23	0.24
Jan	150835	145878	203789	222287	233620	238097	246916	246204
Feb	91611	89131	131348	144545	153120	156552	163296	166609
Mar	83281	79745	118526	126993	132804	135092	139069	158172
Apr	235185	235138	222174	212275	210092	209056	205874	423468
May	617304	622530	575135	545022	536923	533780	526456	837611
Jun	1474560	1429559	1313053	1271066	1264904	1261015	1251300	1608836
Jul	1940658	1877821	1735820	1693345	1688544	1685226	1676167	2014615
Aug	1838304	1767394	1628423	1583467	1576117	1572494	1561989	1901819
Sep	1554162	1495208	1381346	1338437	1331110	1327188	1317140	1667017
Oct	963302	965217	903500	855350	842606	836418	823662	1234735
Nov	259065	269929	240893	221379	214084	211898	205946	448479
Dec	145656	138063	177124	190209	197475	200180	205768	194286

TABLE 12. The comparison of optimization in heat loss and gain.

	Heat loss (wh)	Heat gain (wh)
origin	6663	57753
0.15	5938	61890
0.17	7495	68046
0.19	7790	71114
0.21	8139	72139
0.22	8280	72601
0.23	8531	72558
0.24	7769	100885

Table 12 indicates that the increase of the window area leads to heat loss in winter, but heat gain shows non-constant relationships: e.g., 0.17, 0.19, 0.21, 0.22: the heat gain and heat loss are both rising, and may also fall (e.g.,0.23, the heat is lower than the former optimization). We conclude, then, that there is no direct connection between visible heat loss and building energy consumption. However, with an optimal WFR of 0.23, the building energy consumption is reduced by 11.02%, but it does not reach the target of 30%. Therefore, it is necessary to further optimize building energy consumption by other means.

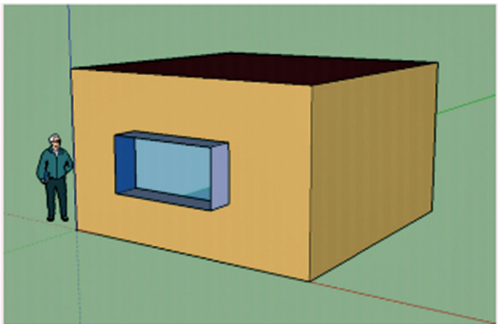
4.3 Further optimization of energy consumption under the green WFR

Sunshade devices. A sunshade device refers to means and measures for obstructing the heat radiation coming from the glass at a favorable angle using specific materials and structures without attenuating the lighting conditions. The protective structure was divided into inner and outer shades. The inner sunshade mainly referred to indoor sunshade curtains, and the outer sunshade included outdoor blinds, roller blinds, awnings, and sunshade structures according to Aguilar *et al.* (2017).

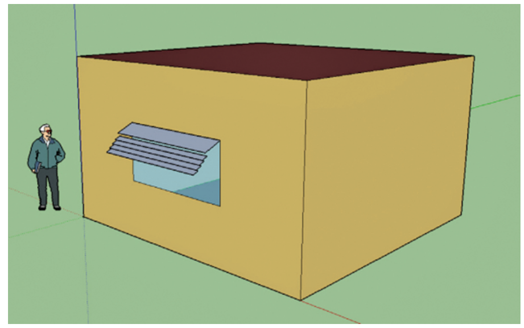
Since the inner shading device was mainly related to the decoration form selected by the owner, this study explored forms of suitable external shading when optimizing the shading of the residential building. External shading was one of the effective methods for energy-saving building design in China's hot summer and cold winter areas, especially in summer, when it blocked solar radiant heat from entering indoors. Moreover, in winter, it could help avoid indoor heat loss. An external shading device could also improve indoor thermal comfort and illumination for residents or building occupants.

Ghosh and Neogi (2018) designed a new form of external shading device for a hot, humid climate by calculating the energy loss of the heating, cooling, and lighting systems of several common external sunshade forms. Through the authors' calculation and analysis, the new sunshade device as in Figure 11(a) had significant advantages in reducing energy consumption of the building. However, due to its unique shape, it was difficult to apply in practical engineering. This study selected a four sidefins shading system as in Figure 11(b) that was second only to the new shading system proposed by Ghosh and Neogi (2018), but far superior to other

FIGURE 11. (a). The new shading design. (b). The four sidefins sunshade device adopted by this research.



(a)



(b)

FIGURE 12. The simplified model with a four-sides sunshade.

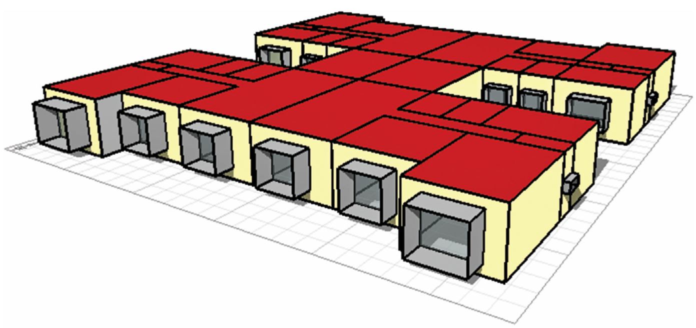


FIGURE 13. Monthly energy consumption of different shading types.

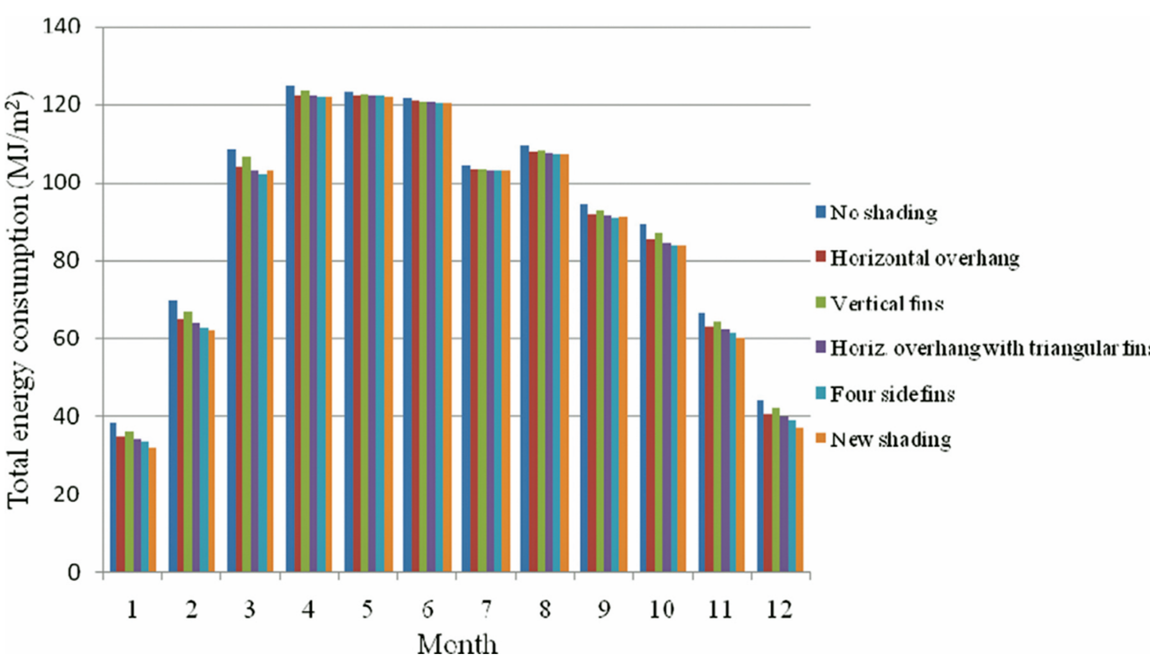


FIGURE 14. The monthly analysis of energy consumption after adding sunshade.

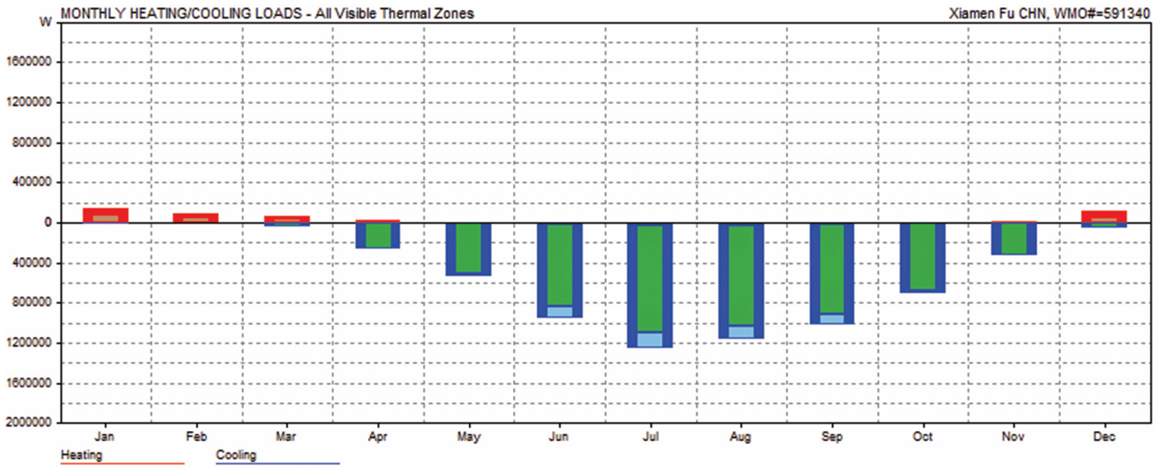


TABLE 13. The relationship between shading tine periods and extension length.

Shading time	7–17	8–16	9–15	10–14	11–13
Extension length	2.76H	1.54H	0.95H	0.57H	0.27H

shading systems in residential building energy performances. Figure 12 presents the simplified model with a four-sides sunshade, and Figure 13 illustrates the monthly energy consumption of different shading types. Figure 14 presents the monthly analysis of energy consumption after adding sunshade.

The size of the four sidefins sunshade device mainly referred to the length of the exterior sunshade. Its design size was primarily controlled by geographic location and sun position. In the study of the optimal length of the outer sunshade of the southern building, Ghosh and Neogi (2018) summarized the relationship between different shading time periods and the length of the sunshade. H referred to the height of the lower edge of the window to the horizontal plate. Table 13 presents the relationship between shading tine periods and extension length.

According to the climatic conditions of Xiamen, the study chose 0.5H as the out-of-line length. After the sunshade was added to the model, the total energy consumption of heating decreased from 8,323,583wh to 6,671,547wh (see Table 14) with a decrease rate of 19.85%. Although the energy consumption of the building was reduced again, the requirement of 30% was still not met, and the glass material was further optimized.

4.4 Analysis on glazing

To overcome the situation that buildings were consuming too much energy, many designers have explored different window configurations using a wide variety of glass types to reduce building energy consumption; Aguilar *et al.* (2017) tested the thermal evaluation of four configurations of double glass window (DGW) coupling to a room. The DGW consisted of two vertical semitransparent walls separated by a 12mm air gap. The descriptions of the four configurations are

TABLE 14. The statistics of energy consumption of heating and cooling after sunshade devices were added.

Month	heating (Wh)	cooling (Wh)	Sum (Wh)
January	139364	0	139364
February	84858	0	84858
March	67984	33009	100993
April	20467	257437	277904
May	0	535817	535817
June	0	949324	949324
July	0	1244968	1244968
August	0	1165198	1165198
September	0	1010860	1010860
October	0	707596	707596
November	13984	320103	334087
December	120578	0	120578
Total	447235	6224312	6671547

presented in Figure 15. For each case, the authors calculated the energy consumption of each room by measuring the optical transmittance and the specific reflectance separately. The results found that Case 1 and 4 were the best choices for energy saving in a warm climate. Considering that there might be glare and discomfort in the use of reflective glass in Case 4 (clear glass+air gap+reflective glass), the Case 2 (clear glass+air gap+absorbent glass) was selected for the further optimization in saving building energy. We then compared the monthly energy consumption before and after the glass materials changed as presented in Figure 16 and Table 15.

After changing the window glass structure for the model with the sunshade and optimum WFR, the overall energy consumption was analyzed in Table 15. The total heating energy

FIGURE 15. Four glass combinations.

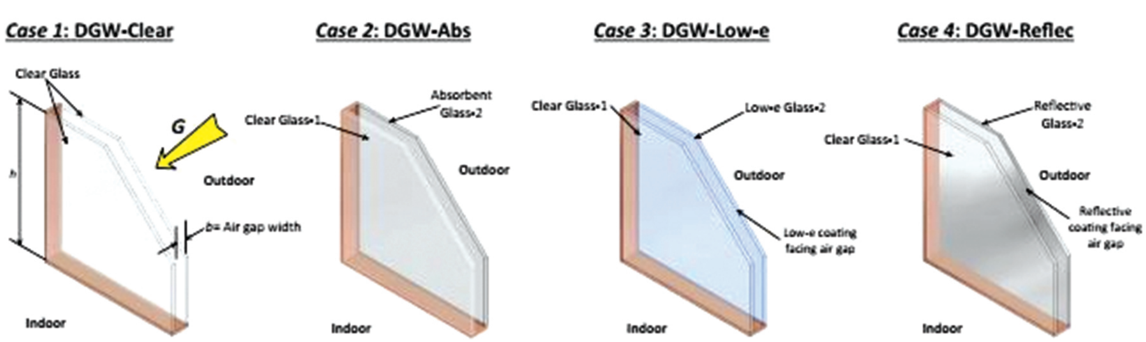


FIGURE 16. The monthly heating/cooling loads after the change of glass materials.

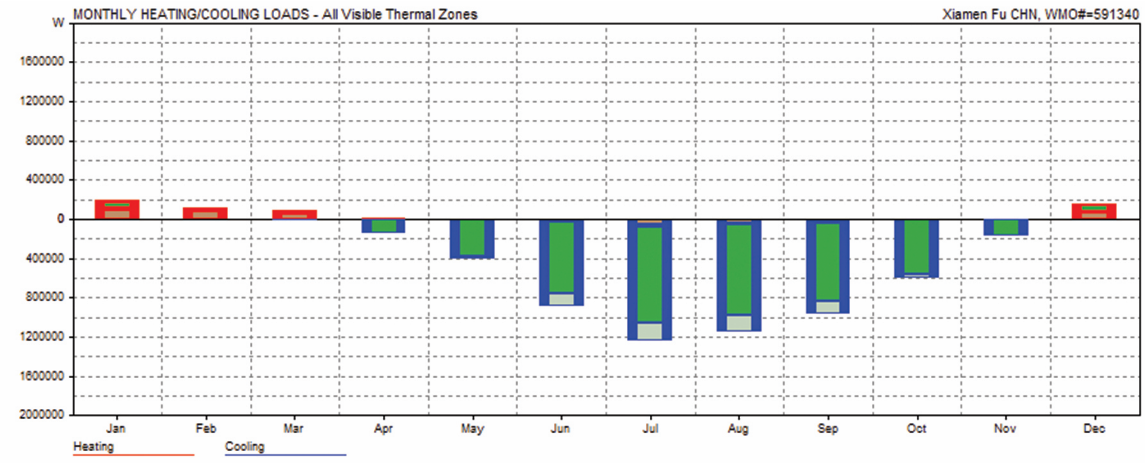


TABLE 15. The statistics of energy consumption of heating and cooling after glass materials be changed.

Month	heating (Wh)	cooling (Wh)	Sum (Wh)
January	190676	0	190676
February	121349	0	121349
March	85401	11276	96677
April	13454	142172	155626
May	0	402965	402965
June	0	885172	885172
July	0	1239803	1239803
August	0	1140865	1140865
September	0	967062	967062
October	0	595812	595812
November	3127	167407	170534
December	162718	0	162718
Total	576725	5552534	6129259

consumption decreased from 6,671,547 wh to 6,129,259 wh, a decrease of 8.13%. This section optimized the energy consumption of the simplified model with the optimal WFR of 0.23. Further optimization methods included adding sunshades and altering window glass structure to double-glazed with a 30mm air layer. The total building energy consumption decrease rate was 34.47% compared with the initial model, which was greater than 30%, thus achieving the optimization goal.

5.0 CONCLUSIONS

It is widely acknowledged that air conditioning accounts for more than half of building energy consumption, and 50% of heat is lost through doors and windows. Changing the size of windows is an easy and practical optimization measure. Combined with the development status of building energy conservation, this study chose the window area to reduce the building energy consumption as the research objectives. A standard window-to-floor ratio (WFR) for green residential buildings in subtropics was developed, and the results showed that 0.23 was the optimal WFR in the subtropics. Adding four sidefins as sunshade devices and changing the windows to double-glazed with a 30mm air layer were other two auxiliary means for energy saving. Very few studies paid attention to the influence of WFR on building energy under different climatic conditions. The development of BIM made it possible to study specific WFR under climatic conditions and put forward the required window size for different green building regulations. This study contributed to the design of green WFR in subtropics under today's promotion of sustainable development. In the design stage, many factors are affecting the design of windows, but the most direct factor is the window size, which could be determined by climatic conditions, location, and window orientation. Through the study on high-rise residential models, the green WFR was used to reduce the energy consumption of buildings. The proposal for green WFR is necessary and the necessary measures are also in line with social trends and meet the current national measures for building energy conservation. In addition, the case studies were limited to Xiamen city. Ecotect consists of simplified energy simulation tools, which are based on a complex simulation algorithm. When it comes to complicated models, it may take a long time for the computer to run and lead to deviations in the analysis model. It is recommended that further studies on building energy-saving to consider different climatic conditions and different building orientations. Different software can be used for testing the validation in future work.

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