DESIGN OF PUBLIC RENTAL SETTLEMENTS BASED ON GREEN AND LOW-CARBON RESEARCH: EXAMPLE OF COURSE DESIGN FOR A SENIOR DESIGN CLASS

Jing Yang,[1] Wangyi Hua,[1] Tian Xia,[1] Qian Li,[1] Huijie Shi,[1] and Xin Zhou[2,*]

ABSTRACT

Public rental housing has received widespread attention from the government and the public, and with the global response to climate change and the goal of "carbon peak and carbon neutral," the development of green and low-carbon rental housing has become an important trend. Against this background, the design of public rental housing in this project is designed with the hope that students will take the problem as the guide, performance optimization as the means, and start from the perspective of architectural design to explore the combination of low-carbon strategy or green technology and design in order to create low-carbon public rental housing. The paper analyzes and shows four groups of assignments in detail, which, through crowd demand analysis and site analysis, propose corresponding low-carbon driven design solution strategies from four aspects: the design of shared carbon-saving living patterns, the pattern organization of innovative central corridors that facilitate lighting and ventilation, algorithm-driven form generation, and the composite optimization of radiant heat in the façade.

KEYWORDS

public rental housing, green and low-carbon, public-private separation, genetic algorithms, radiant heat on facade

1. BACKGROUND OF THE SUBJECT

In China, the most prominent housing issue is the mismatch between supply and demand in large cities. The mismatch between housing prices and income and the inadequacy of the rental market have led to housing difficulties for new citizens, young people, and other groups. To solve the housing problem in big cities, public rental housing, which is an essential part of the construction industry, has received extensive attention from the government and citizens. Continuously upgrading the capacity of public rental housing and the development of public rental housing will help alleviate housing problems and is the top priority for the construction of protected housing.

Owing to the global response to climate change and to achieve the goal of carbon peak and carbon neutrality, the construction industry, as a "big player" in carbon emissions, has started

1. School of Architecture, Southeast University, Nanjing, Jiangsu Province 210096, China
2. 1493162046@qq.com (corresponding author)

green transformation and development. Rental housing, a vital segment of the construction industry, benefits from policy support and guidance for its green and low-carbon development, which is an emerging trend. Such green, low-carbon rental housing plays a demonstrative and promotional role in green economic development and the transformation of housing construction methods in China. The essence of the development of green, low-carbon rental housing is to introduce the concept of "green" into the field of rental housing, starting from the demand of residents and focusing on the use of the living space to reduce carbon emissions during the entire life cycle of rental housing in order to provide tenants with a livable, low-carbon, and green living environment.

2. CHARACTERISTICS OF SUBJECT SETTING

In 2021, the General Office of the State Council issued Opinions on Accelerating the Development of Guaranteed Rental Housing, which clearly stated that rental housing would mainly solve the housing difficulties of eligible new citizens, young people, and other groups and would be dominated by small households with a floor area of no more than 70 square meters. Given the high-intensity residential development and a focus on increasing small household proportions, high-rise corridor-type housing is frequently selected as a typical model for public rental housing in China. In the case of high-rise corridor houses, especially medium corridors, the lighting and ventilation of the indoor and outdoor environments face many challenges, which in turn affect the green and low-carbon levels of these public rental houses.

In this context, the public rental housing setup in this project is mainly for newly employed homeless workers, prospective college-graduate employees, newly employed low-income youths, and individuals with a few years of stable employment. The base selected was Nanjing Xuzhuang Software Park, mainly for residential support for the park, which serves many young employees. The plot ratio of the subject base site is 2.5, which is high-rise gallery-type public rental housing. The focus was on the design of house types and public support facilities that meet the needs of young people in rental settlements, as well as the use and expression of low-carbon thinking in the design of public rental housing. The specific features of this topic are as follows:

2.1 Problem-oriented and demand-driven

To understand the construction and use of public rental housing in China, we focused on the characteristics and needs of the population and explored the existing design and usage issues to develop targeted solutions. The analysis of the primary causes of high energy consumption in public rental housing helps the selection of effective natural energy applications in buildings from a demand perspective and the creation of low-carbon, public rental housing through architectural design.

2.2 Performance control methods

The performance control method involves the use of building performance simulations in design and software for staged analysis and collaborative work, with timely design feedback optimizing building plans. The simulations in this project focus on indoor and outdoor wind, light, and thermal environments. Interventions in the design phase include green performance management, aligning design processes with simulation practices, selecting suitable software, and establishing a data conversion method across different programs. This method integrates building physics into the design process, aiding students in modeling and simulation for scientific designs.

2.3 Multi-objective optimization design method

For different design objectives, the building design model was linked with parametric performance analysis tools to weigh multiple performance objectives and formulate optimized design decisions to achieve the green and low-carbon goals of public rental housing under complex constraints and on the premise of satisfying building performance. For example, in the site design stage, building layout and height control are combined with sunlight and ventilation; in the single unit design stage, comprehensive optimization of climate-adapted building skin and indoor light and heat environments are carried out; and in the tenant room allocation, linkage analysis of room characteristics and physical characteristics of user comfort is carried out to achieve comprehensive analysis and optimization of comfort and energy saving in the use stage.

2.4 Highlighting design strategies for low carbon

This project combines low-carbon research with conventional architectural studies in the master plan, functional layout, spatial organization, house design, etc. and changes the status quo of previous architectural designers designing first and technicians intervening in the simulation later. The course design guides students to think about the combination of low-carbon strategies (including green technology) and design from preliminary crowd demand and site analysis, and throughout the entire design process, to make the entire process of architectural design driven by low carbon objectives.

3. PROJECT RESULTS (MULTIDIMENSIONAL RESEARCH STRATEGIES)

By analyzing and summarizing the characteristics and problems of public rental housing, the five groups of students in this course adopted problem-oriented and performance optimization as a means to propose different design solutions from four aspects: the design of a shared carbon-saving living mode, pattern organization of an innovative central corridor that facilitates lighting and ventilation, algorithm-driven generation of forms, and composite optimization of radiant heat in the façade.

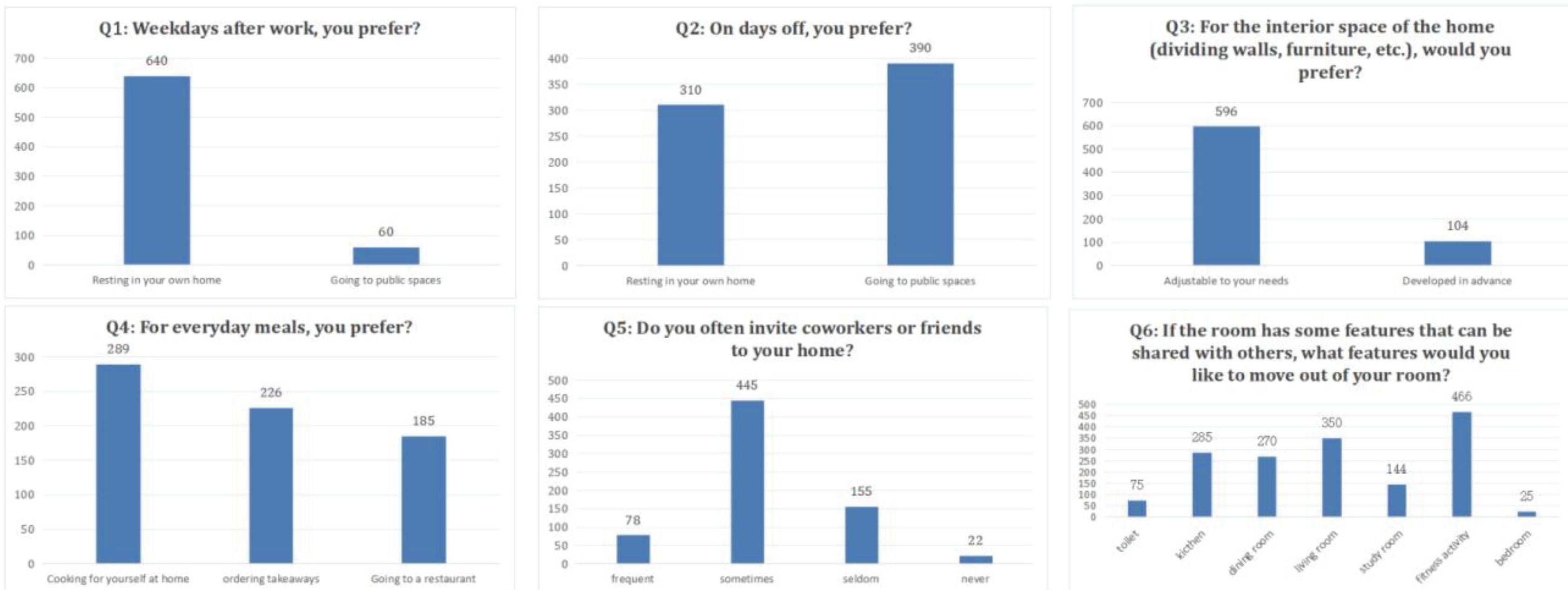
3.1 Shared lifestyle and low carbon

As a type of small-space residence, the quality of public rental housing is no longer measured solely by the size of the household; it reduces the amount of personal nonessential space and increases the amount of socially diversified and secure space, thus achieving the goal of making private space more personalized and life security more socialized. This is shifting part of the demand for living spaces to socialized sharing by releasing some of the public functions within private households to form composite-function settlements and shared spaces in residential buildings. By encouraging residents to make greater use of shared public spaces, energy can be shared, thereby reducing the waste caused by "repetitive" energy consumption.

3.1.1 Situation analysis and needs study

Hua Wangyi et al. first investigated the needs of public rental housing users. Aiming at prospective college-graduate employees, newly employed low-income youths, and individuals with a

FIGURE 1. Survey questionnaire data analysis.



(Figure source: self-drawn)

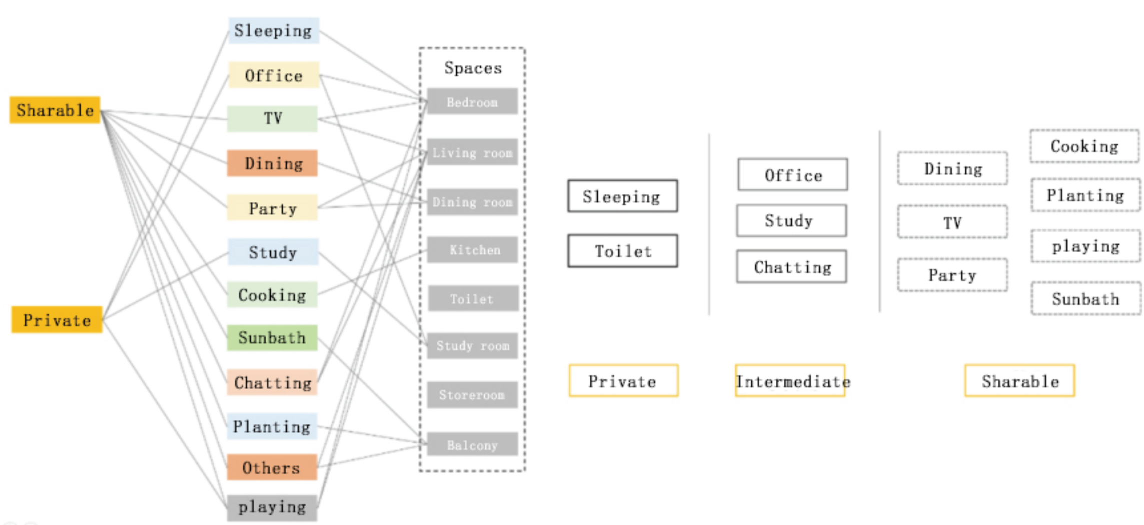
few years of stable employment, they conducted network research on the type of public rental housing and the design of public spaces. A total of 750 questionnaires were distributed, of which 700 were valid, with a balanced ratio of 1:1 between men and women.

Six representative questions were selected from the questionnaire for analysis, as shown in Figure 1, which reveals that (1) most young people present two different living conditions on weekdays and days off and are more inclined to rest indoors or move around in the public space near their residence after work on weekdays. On days off, they choose to go to a larger public space for recreation and socialization. (2) The proportion of young people who choose to cook at home and meet guests was relatively low. The prioritization of functional spaces that can be shared was as follows: fitness activities > living room > kitchen > dining room > study > bathroom > bedroom. (3) Most young people hope that the interior space of a house is variable and can be adjusted according to their own needs rather than being designed in advance.

The above research on living patterns has prompted the design of this course to consider variable residential use patterns, decentralized public facilities for activities and rest in close proximity, as well as the shaping of a more significant level of aggregated public space, as shown in Figure 2, which analyzes the behavioral patterns of the residents, and explores the sharing pattern of living behaviors by moving fitness activities, the living room, the dining room, the kitchen, and the study out of the "private room" on demand according to the size of the house, and the personality of the user.

The literature and research data show that (1) the needs, habits, and characteristics of residents living in high-density communities are different from those of other low-density communities, leading to lower per capita carbon emissions in high-density communities, which is more conducive to the reduction of carbon emissions. (2) In the case of an equal total population, large-scale collective living results in lower per capita carbon emissions, as members share activities and equipment within a specific time and space. (3) The abundance and accessibility of public services in the community are negatively correlated with residents' total carbon emissions,

FIGURE 2. Residents behavior pattern analysis. (Figure source: <Exploration of Living Space and Dwelling Mode under the Perspective of Sharing Economy> by Chang Mingwei, Yuan Dachang)



due to the reduced transportation energy used for travel. (4) Carbon emissions occur mainly at home, and family life is the primary source of carbon emissions [16].

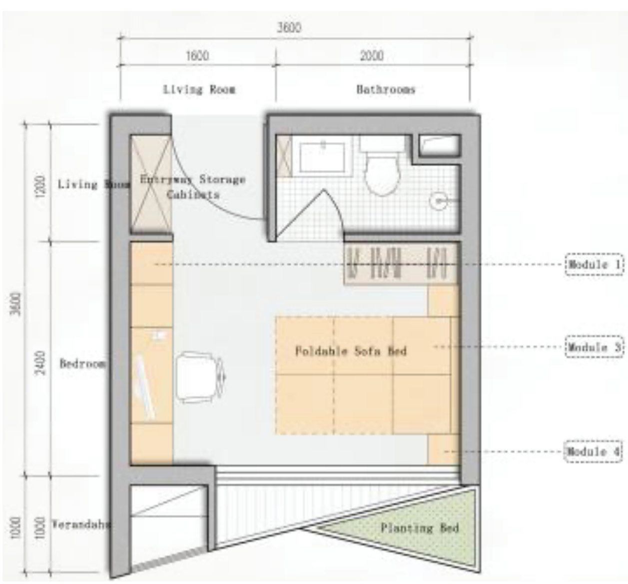
The public rental housing studied in this design is a typical example of a high-density residential community. In terms of the building level, if the shareable space is extracted from the independent room (unit) and dispersed on each floor, which encourages the residents to go out of the house, the "collective life" of the building level or even the settlement level can be promoted so that the shared energy consumption is shared equally, which is conducive to the reduction of the per capita carbon emission.

3.1.2 Design Optimization Strategies

Based on the study of crowd behavior patterns, Hua Wangyi et al. divided the shared space system into three levels: the community level, that is, the ground floor public space, was open to residents and outsiders, providing functions such as supermarkets, convenience stores, express delivery, snacks, recreation, community healthcare, catering, and a furniture module market (which can be used to select the right size of furniture for creating indoor space on its own), and the building level, where each building had its own dedicated space and shared space, having functions such as meeting guests, kitchen, laundry, and drying. Lastly, at the tenant level, 3.6m was chosen as the module, and several 3.6m × 3.6m interest spaces were designed, which included themes of learning, fitness, screening, games, and art and were placed into the buildings according to the ratio (2:2:1:1:1) of young people's interests, which were based on a questionnaire survey.

At the household level, ranging from single rooms to shared and family rooms, we analyzed the different behavioral patterns according to varying economic conditions and family structures and combined with the results of the questionnaire survey. The priority of the shareable functional space was public activities > living room > kitchen > dining room > study > bathroom > bedroom, and different numbers of functional rooms were extracted according to

FIGURE 3. Capsule model (13 m^2).



(Figure source: self-drawn)

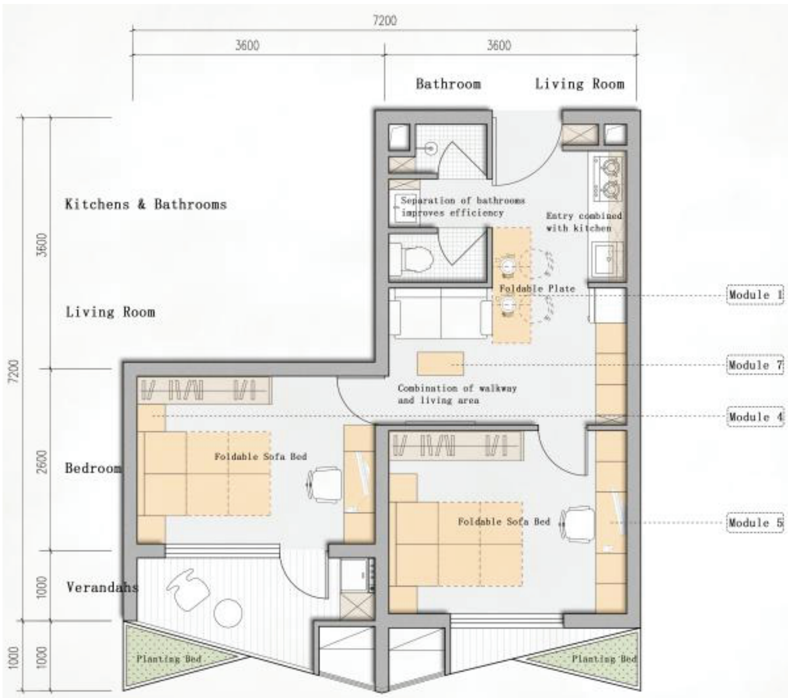
the differences in demand. Based on the differences in demand, different numbers of functional rooms were extracted and placed in shared spaces, and four different house types were designed. Simultaneously, shared spaces that complemented the functions of the house were set up outside the house types of varying size segments to achieve a balance between outdoor shared functions and private functions inside the house.

For single youths with weaker economic power, as shown in Figure 3, the 13 m^2 capsule room only guarantees their basic privacy needs. Based on the questionnaire data on the population pattern, other shareable functions in the house type, except for the bedroom and bathroom, were extracted and placed into the shared public space. These shared spaces were evenly distributed on the floor, prompting people to leave their rooms for sharing. For single youths or couples who have a certain amount of financial strength and are more in pursuit of quality of life, as shown in Figure 4, the 26 m^2 one-bedroom, one-bathroom unit has a certain amount of “interest corner” space (i.e., a collection corner, communication corner, study corner, etc. that

FIGURE 4. One-bedroom, one-living room model (26 m^2)

(Figure source: self-drawn)

FIGURE 5. Two-bedrooms, one-living room model (39 m²).



(Figure source: self-drawn)

meets the needs of each individual) and a dining space compared with the capsule room. More publicized functions such as dining, fitness, and reading remain in shared areas of the building.

For couples with children and friends sharing a room with two people, as shown in Figure 5, the 39 m² two-bedroom, one-bathroom house types can achieve a balance between shared living and comfortable living in a limited area. Most of the space in the house type is the bedroom and bathroom for privacy. In contrast, the space available for sharing, such as the living room and dining space, is compounded as much as possible to utilize the transportation space, such as the aisles, encouraging residents to make more use of the shared space in the residential building. Similarly, the 52 m² house types for families or higher-income tenants (Figure 6) feature larger household common spaces for basic activities, while still promoting the use of shared spaces in the building or settlement for a richer living experience.

At the dwelling-building level, the focus is on the balance between shared outdoor and private indoor functions. As shown in Figure 7, the northern building mainly comprises 26 single-bedroom rooms. Considering the lack of a large kitchen, dining space, and meeting space inside the house, the meeting, dining, and interest space modules are staggered in this house group. At the same time, the western building mainly arranges 52 m² variable-type family rooms. Because the family room already covers a more comfortable dining and meeting space, three larger activity spaces with greenery are spaced out in the middle corridor of this house-type group by using a sawtooth shape to facilitate neighborhood activities and exchanges; the southern building mainly arranges 13 m² capsule rooms and 39 m² shared rooms, both of which are more intensive house types. Considering that the functions of the household can only meet basic life activities, this household group has more demand for shared space; in addition to the

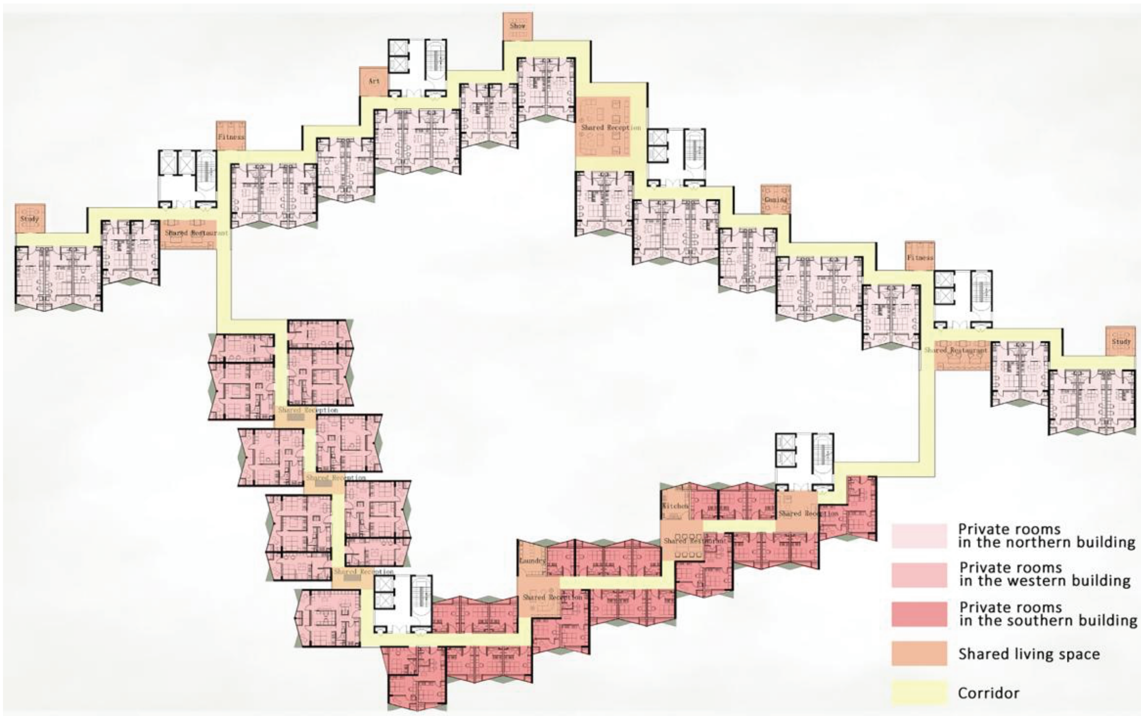
FIGURE 6. Family variable model (52 m²).

(Figure source: self-drawn)

meeting, dining room, and interest activity modules, additional functional modules such as laundry and kitchen are set up, and the capsule room of the same 13 m^2 can be replaced with the interest activity module when it is unused to meet the more flexible shared life mode.

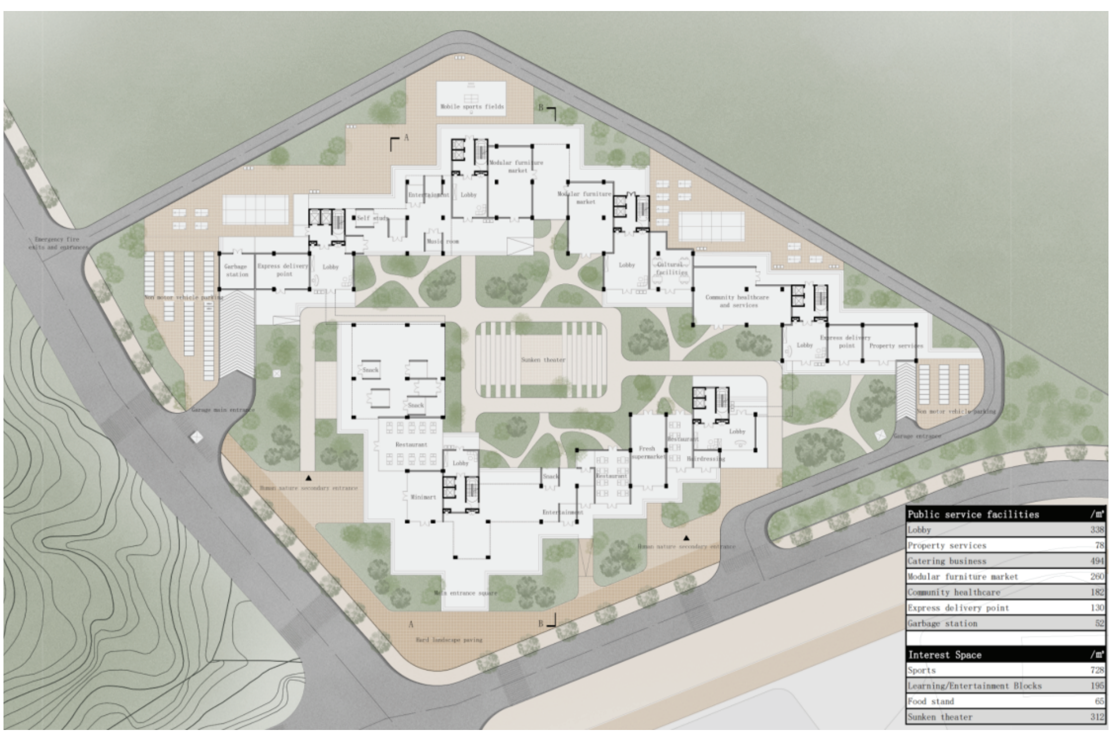
At the settlement level, the ground floor consists of mainly of public service facilities, hobbies, activity areas, and living markets that are open to residents and outsiders. The rich and complete community support space on the ground floor covers almost all the functions required for a 15-minute living cycle (Figure 8), which significantly reduces the transportation energy consumption of residents seeking service facilities in other areas. At the same time, the large greenspace arrangement within the district provides a rich landscape element and contributes to low carbon and energy savings for the community.

FIGURE 7. Shared and private spaces on the residential level.



(Figure source: self-drawn)

FIGURE 8. Shared space ratios at the settlement level.



(Figure source: self-drawn)

3.1.3 Summary

The foregoing design analysis reveals that a shared living mode is a powerful development point for promoting low-carbon and energy-saving settlements. This mode can not only achieve a balance between energy-saving and socialization and between land-saving and comfort but also drive the low-carbon and energy-saving of the whole region with the settlement as a "point." It also has operational and research significance for future changes in household size and even the replacement of functions in the settlement. Future research can further analyze the energy consumption simulation of the shared housing and traditional housing models to quantitatively reveal the advantageous characteristics of the shared housing model in terms of energy savings and carbon reduction.

3.2 Innovative organization of the central corridor for lighting and ventilation

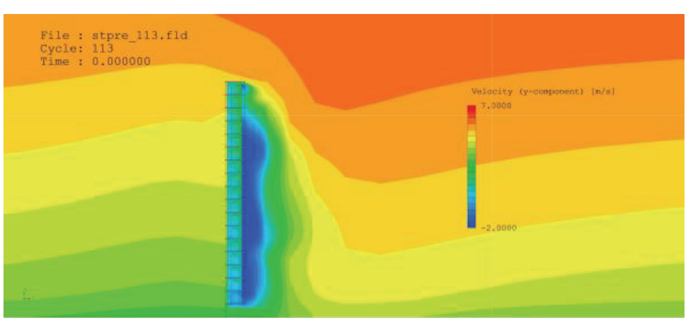
Several attempts have been made to obtain better natural light and ventilation in terms of orientation and form. However, the rapid growth of the urban population and shortage of residential land have made buildings constantly taller and longer, with the inevitable form organized in the middle corridor. However, in this mode, difficulties in indoor ventilation, wind field disorder between buildings, and many other adverse effects are often encountered; therefore, a new high-density building organization that is conducive to lighting and ventilation should be urgently explored.

3.2.1 Analysis and study of the current situation

According to the literature, excessively long high-rise public housing produces large, continuous shadow projection areas. The characteristics of small household size and dense population make high-rise public housing settlements not only more crowded and chaotic but also form large-area wind shadow zones, architectural airlock effects, wind vortices, and other phenomena, which cannot obtain better inter-group ventilation effects [19]. In particular, the indoor ventilation effect is poorer in houses that are ventilated only by a single window without a patio or notches on either side [18].

Li Qian et al. established a model of a high-rise building with patios and wind environment simulation in this site environment based on the results of their study. As shown in Figure 9, in the high-rise building with patios, the ventilation of the corridor is smooth, but producing the phenomenon of blocking the ventilation corridor in the leeward part of the building is easy, thus forming a significant wind shadow area.

FIGURE 9. Wind speed in cross-section of high-rise center corridor building.



(Figure source: self-drawn)

FIGURE 10. Low-carbon settlement subject design for light and ventilation.

(Figure source: self-drawn)

3.2.2 Design Optimization Strategies

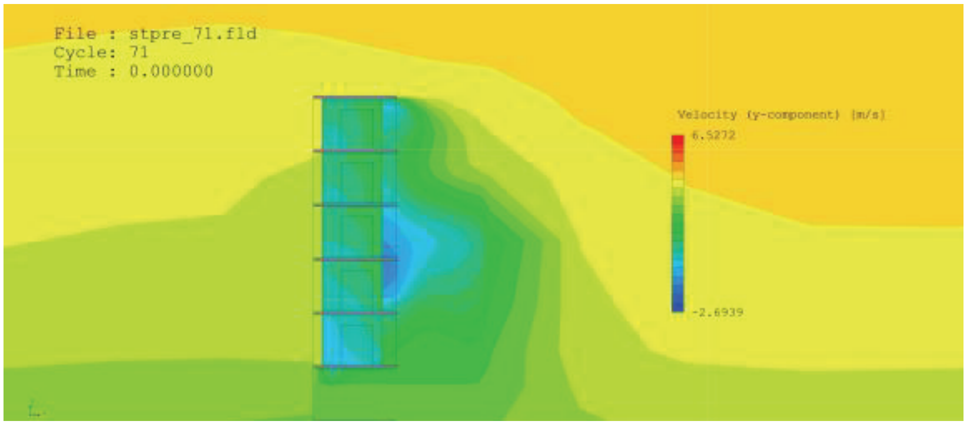
To improve the effect of lighting and ventilation in the settlement, the quality of space in the settlement and units, and reduce energy consumption, this course design mainly attempts to improve the design scheme from two aspects: the morphological layout of the residential building and the optimization of the space of the central corridor. The overall form after the improvement is shown in Figure 10.

1. RESIDENTIAL FORMATION TO ZERO: CONVERSION TO A MULTISTORY BUILDING MIX THAT FACILITATES VENTILATION IN THE CENTER CORRIDOR.

A high-rise central corridor-type building not only easily blocks the airflow, resulting in a disturbance of the internal wind field of the settlement, but is also not conducive to the ventilation of the central corridor and rooms on both sides, which affects the comfort of the human body [19]. Therefore, Li Qian's group tried to interrupt the continuity of a high-rise building, turn the entire building into pieces, unclog the internal airflow, and improve the ventilation of the building.

The strategy of interrupting high-rise residential buildings was inspired by the Jade City New View in Singapore, which adopted the practice of stacking multistorey residential buildings into high-rise buildings. To verify the effect, two models—a 6-storey mid-porch building and a 21-storey high-rise mid-porch building—were established, and the wind speeds at the lower floors of both types were measured separately. Typical sections of equal heights at the patio and non-patio locations in the two models were selected for the comparison of the specific wind speeds measured. After data comparison, as shown in Figure 11 and Figure 12, the wind speed of a single multistorey center corridor building at the same height as the low floor is better than that of a single high-storey center corridor building, and the difference between the two can reach 0.01–0.7 m/s. This result verified that the improvement measures could achieve a better ventilation effect.

FIGURE 11. Wind speed in cross-section of multistorey center gallery building.



(Figure source: self-drawn)

FIGURE 12. Comparison of cross-section mean wind speeds of multistorey and high-rise center corridor dwellings.

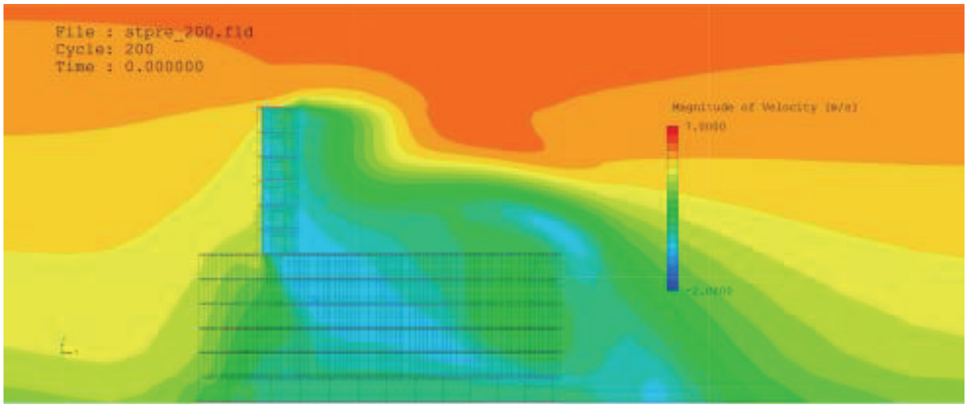
		Patio location cross section		Non-patio location cross section	
Type of building		Multi-storey building	High-rise building	Multi-storey building	High-rise building
Wind speed on the same floor (m/s)	1F	2.53	2.09	2.64	2.16
	2F	0.786	0.086	0.832	0.164
	3F	0.761	0.296	0.802	0.371
	4F	0.858	0.436	0.815	0.423
	5F	1.076	0.492	1.127	0.513
	6F	1.12	0.64	1.24	0.687

(Figure source: self-drawn)

Further quantitative comparisons of the ventilation of the combined multistorey center corridor building and single high-rise center corridor building were made using the cross-sectional wind speed at the exact location on the middle and high-rise floors as the evaluation index, as shown in Figures 13 and 14. The comparison shows that the wind speed of the combined multistorey center corridor building is slightly higher than that of the single high-rise center corridor building at the exact location on the middle and high floors, and the ventilation effect is marginally better. In addition, from the simulation results of the wind environment at the site, high-rise buildings with multistory combinations do not form a significant wind shadow area, which is a more friendly choice for the wind environment of the community.

Based on the above conclusion and a plot ratio limit of 2.5, the high-rise corridor houses were divided into a group of ten 7-storey houses, comprising seven single-corridor houses facing south and three medium-corridor houses facing east and west. The overall shape of the staggered layout was open in the direction of the sunshine, and the overlapping method was adjusted based on the duration of sunlight. In the adjustment of the wind environment, considering that the dominant wind direction of the site is southwest in summer and northeast in winter, as

FIGURE 13. Cross-sectional wind speed of multistorey combined center-corridor building.



(Figure source: self-drawn)

FIGURE 14. Comparison of cross-section mean wind speeds of multistorey and high-rise center-corridor dwellings.

		Patio location cross section		Non-patio location cross section	
Type of building		Combined multi-storey building	Single high-rise building	Combined multi-storey building	Single high-rise building
Wind speed on the same floor (m/s)	7F	0.788	0.650	0.821	0.66
	8F	0.915	0.886	0.891	0.845
	9F	0.926	0.936	0.961	0.944
	10F	1.036	0.938	0.994	1.000
	11F	1.067	1.041	1.023	1.054
	12F	1.141	1.075	1.154	1.100

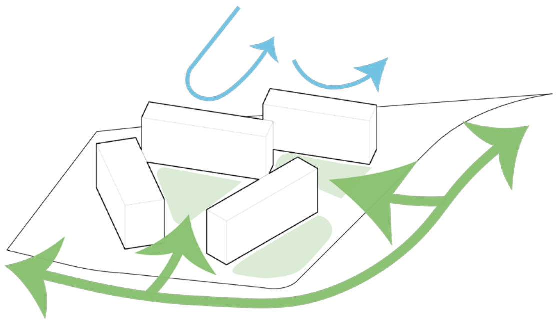
(Figure source: self-drawn)

shown in Figure 15, according to the principle of channeling the wind in summer and blocking it in winter, the wind openings at the height of the main pedestrian activity space on the ground floor were opened to the southwest side to bring the summer wind into the interior. In contrast, the openings were open on the inside of the northeast side to form a turning point and shelter for the winter wind. Simultaneously, the height of the continuous building mass was controlled by avoiding the upper and lower residential buildings in the same direction during the active arrangement. In the form-adjustment process, feedback superposition of the test data was used to obtain the final optimal layout (Figures 16 and 17). This layout offers excellent activity space and three-dimensional greenery for the settlement, thereby enhancing ventilation and lighting conditions.

2. OPTIMIZATION OF CORRIDOR SPACE IN RESIDENTIAL BUILDINGS—PATIO SIZE AND LOCATION OPTIONS

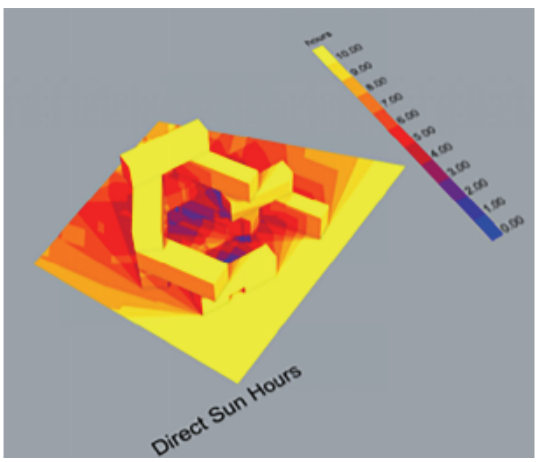
Many studies have been conducted on corridor patio ventilation at the building plane ventilation organization level. The decentralized arrangement of openings in the patio plan has been

FIG. 15. Responding to wind Duration.



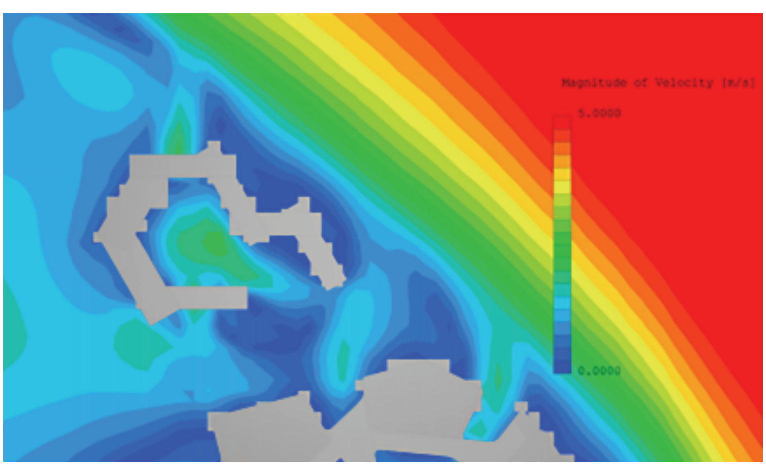
(Figure source: self-drawn)

FIGURE 16. Winter solstice sunshine direction.



(Figure source: self-drawn)

FIGURE 17. Settlement wind environment.



(Figure source: self-drawn)

shown to be better than the centralized arrangement, and a consistent relationship with the position of the windows is required so that the horizontal airflow can penetrate better [9]. Qian et al. optimized the specific shape of the inserted patio to optimize the space of the central corridor further after the form of the building was reduced to zero.

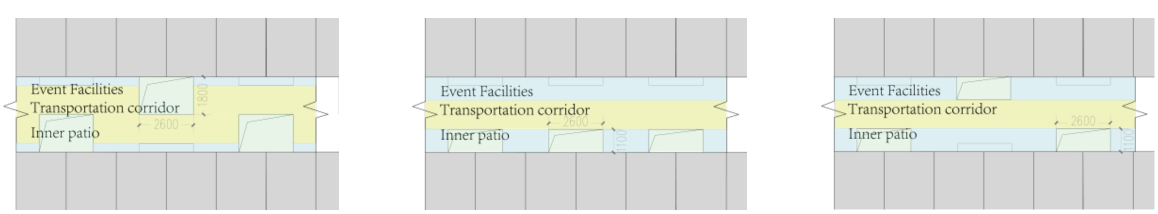
The ventilation effects of the different patio patterns were simulated and compared, as shown in Figure 18. Notably, when no horizontal opening exists in the inner plane, the indoor wind environment of the middle unit cannot be improved. Therefore, in the analysis process, openings were first set up on both sides of the center corridor, and then the patio was set up based on the location of the unit windows. Since the width of the residential building should not be too large, considering the unit face width, entry space, and leaving a corridor space of 1.4m width, this time, a small patio with a cross-sectional area of 2.6m × 1.1m is used, and several small patios are used in a decentralized layout mode.

Three plan layout forms are used in the program interpretation process. Layout 1: staggered set up patio and expanded depth to 1.8m, no central corridor space, relies on the staggered activity space to turn the traffic; Layout 2: set up patio along the side of the unit, the center is the traffic space, and the other side is the activity space; Layout 3: staggered set up patio along the two sides of the unit, to form the central corridor space and the staggered activity space. Three layouts were simulated and compared to the wind environment.The simulation results reveal (Figures 19–23) that in the three layouts with the addition of the patio, the wind speed in the inner corridor can be more than 0.7 m/s, and the static wind area is small; thus, the indoor environment can form a good ventilation environment. A comparison of the three layouts shows that Layout 2, with a continuous row of single-sided patios, smooths the ventilation path and that the average wind speed is relatively high overall. Layout 1 has a relatively inferior overall ventilation environment because of the expansion of the patio size and the weakening of the patio spacing area. Layout 3 has the lowest overall wind speed in the center corridor owing to the small size of the patio and spacing area. However, note that overall, the difference in the average wind speeds of the three layout methods is not significant, with the difference being within the range of 0.5 m/s. The average wind speeds for the three layouts are listed in the following table. In addition to the wind environment, the corridor spatial effect, arrangement of the activity area, and convenience of transportation must be considered; therefore, Layout 3 is chosen as the final program.

3.2.3 Summary

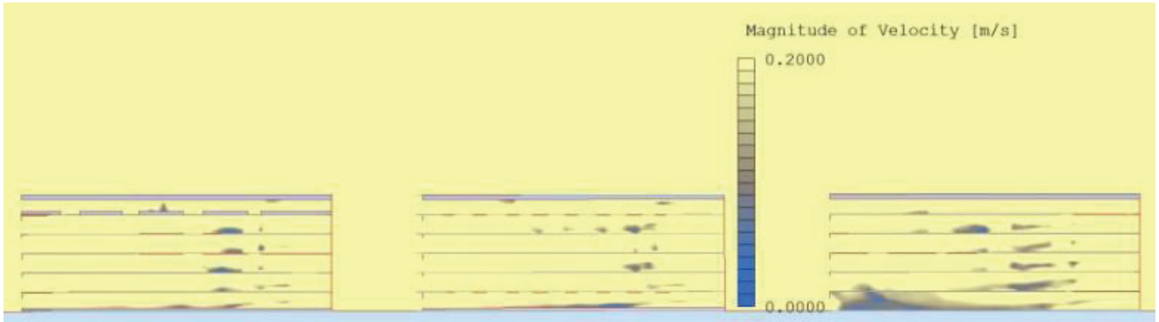
To reduce the negative physical environmental impacts of corridor-shaped buildings in high-rise buildings, the design of this project is an attempt to divide high-rise buildings into fractions and set up staggered patios. Simulation experiments confirmed the effectiveness of this approach in

FIGURE 18. Layout 1, Layout 2, and Layout 3 patio layout approach.



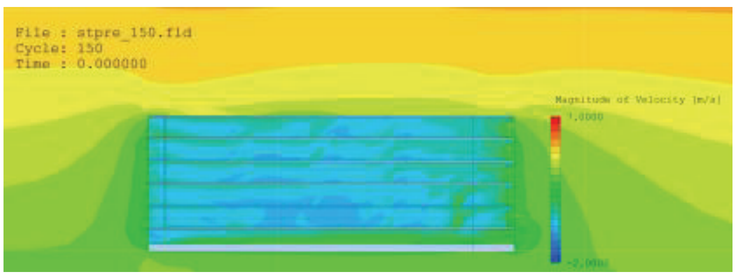
(Figure source: self-drawn)

FIGURE 19. Layout 1, Layout 2, and Layout 3 wind environments simulating static wind zone conditions.



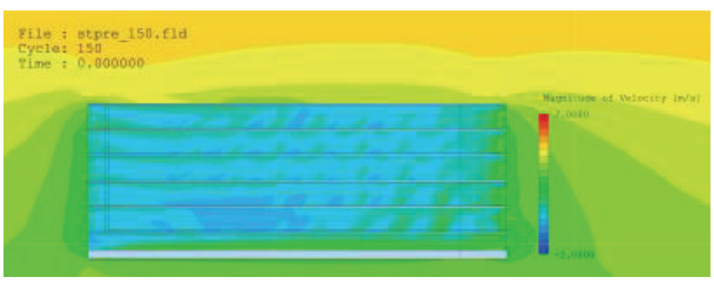
(Figure source: self-drawn)

FIG 20. Simulation of wind environment in the inner corridor of Layout 1.



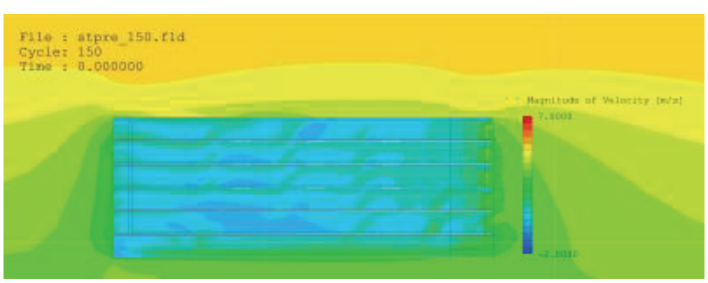
(Figure source: self-drawn)

FIGURE 21. Simulation of wind environment in the inner corridor of Layout 2.



(Figure source: self-drawn)

FIGURE 22. Simulation of wind environment in the inner corridor of Layout 3.



(Figure source: self-drawn)

FIGURE 23. Comparison of cross-section mean wind speeds for three layouts of buildings.

Patio Layout Types		Layout 1	Layout 2	Layout 3
Wind speed on the same floor (m/s)	1F	2.135	1.841	1.641
	2F	0.550	0.659	0.487
	3F	0.648	0.767	0.749
	4F	0.887	0.991	0.862
	5F	1.001	1.023	0.915
	6F	1.230	1.169	1.200

(Figure source: self-drawn)

enhancing indoor ventilation. However, implementation revealed design deficiencies, such as varying housing forms within the same site affecting the organization differently. These layout changes alter the micro-environment of settlements, making this design a simplified treatment of complex overlapping relationships. Therefore, although the experimental comparison results of simple control variables in this design reflect the improvement effect to a certain extent, more specific and detailed comparative calculations should be performed for various layout methods in specific site environments to obtain the particular design effect.

3.3 Algorithm-driven Form Generation

The form of a building is a critical factor in residential design. The layout and form of a building largely determine its overall lighting, ventilation, and other physical environments. A suitable building form can provide an excellent physical environment for residents and reduce the energy loss caused by an inappropriate physical environment during the residential process.

Starting from the form of the building, living problems caused by unfavorable ventilation and lighting can be partly solved. Therefore, this design analyzes the current situation of the physical environment of the site and improves the residential physical environment using the building form as the overall starting point.

3.3.1 Analysis of Site Physical Environment

1. THE OVERALL WIND SPEED OF THE SITE IS LOW IN SUMMER AND HIGH IN WINTER.

Although the wind corridor formed between the mountain on the west side of the site and the site provides relatively good ventilation to the central and western parts of the site, the average wind speed at a height of 1.5m at the site in summer is only 2.2 m/s, and the building clusters on the south side of the site have a windproof effect on the southeast part of the site, as shown in Fig. 24 (a).

Because the northeastern side of the site is flat and no ground buildings are present, the average wind speed is higher in winter. In winter, the average wind speed at a height of 1.5m is 4.47 m/s, and a few areas with wind speeds greater than 5 m/s exist, as shown in Figure 24 (b).

This analysis confirms that the site wind environment has the current situation of low wind speed in summer and high wind speed in winter. The ventilation environment of the site has a significant impact on the thermal environment inside the house; therefore, the wind environment of the site can be changed through the optimization of the building form in the design. In summer, the overall wind speed of the site is mainly improved, especially in the quiet wind

FIG. 24 (a) Simulated cloud image of summer monsoon (Figure source: self-drawn). (b) Simulated cloud image of winter monsoon.

(a)

(b)

(Figure source: self-drawn)

area in the southeast corner. In contrast, in winter, the problem of wind shielding at the site is primarily solved to block the cold current and potential pollutants effectively.

2. SUNLIGHT OCCLUSION EXISTS ON THE SOUTH SIDE OF THE SITE.

On the southern side of the site are high-rise commercial buildings with an average height of approximately 70m. The local area on the south side of the site is affected by it, and no direct sunlight is present for a fixed period.

Therefore, the influence of the south building cluster on internal light at the site was considered to reduce the impact of the south building cluster. Under the standard of minimum sunshine duration during the winter solstice, the sunshine duration of the entire building in winter should be improved and that in summer reduced, mainly by reducing the adverse effects of the west sun on the indoor thermal environment.

3.3.2 Optimization Design Strategy

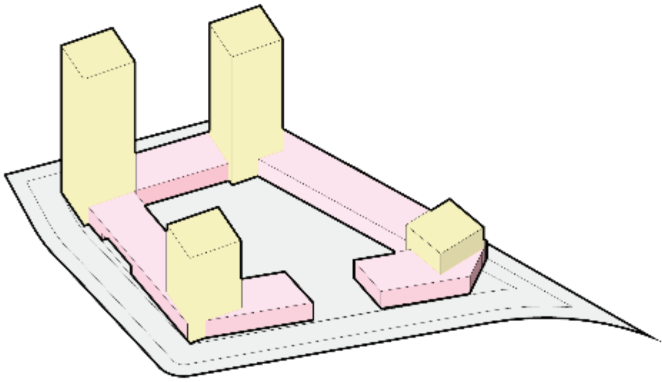
1. ALGORITHMS ASSIST IN BUILDING FORM GENERATION.

The shape and organization of buildings are constantly changing. Conducting numerous model-by-model analyses to examine physical environment variations under different building forms is time-consuming and inefficient, making the identification of the optimal form combination challenging.

Therefore, two students, Shi Huijie and Chai Kailin, used genetic algorithms to assist in form generation. By setting a number of independent variables related to the building form, the algorithm was carried out to simulate and calculate the physical environment results of all the building forms and find the optimal solution according to the environmental indicators to improve the design efficiency and accuracy.

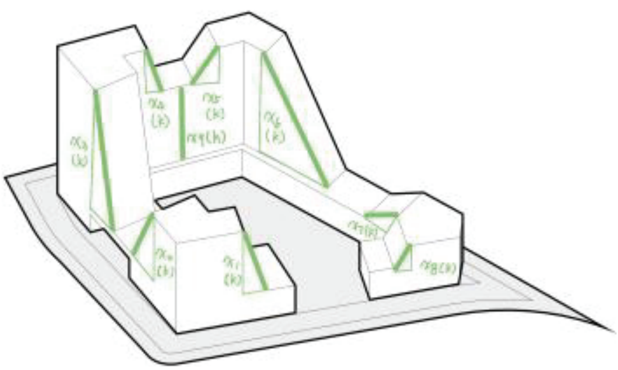
First, according to the sunshine and wind environmental conditions of the site and personal design intentions, the position and height of the building volume were roughly determined from

FIG. 25 Basic building form.



(Figure source: self-drawn)

FIG. 26 Independent variables x1-x9.



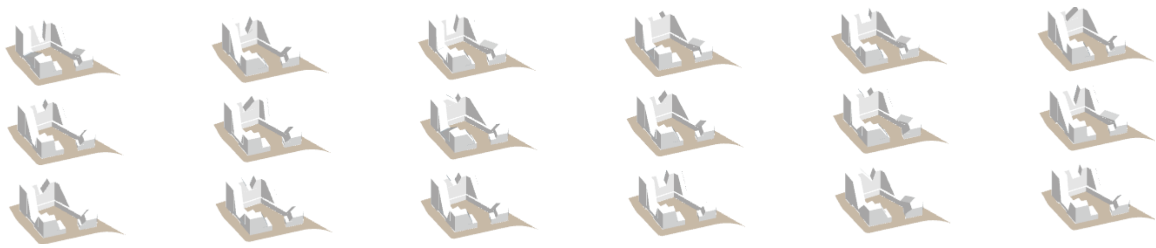
(Figure source: self-drawn)

the perspective of occupying the advantages of the physical environment, and a basic building form was generated, as shown in Figure 25.

Second, to optimize the physical environment around the building and increase the amount of construction, extension, and expansion of the building blocks are considered. As shown in Figure 26, the slopes of the sides of the four building monomers are taken as variables x1-x8, and the local height of the building is taken as variable x9. Nine variables are extracted; the feasible domain of the variables is determined according to the possibility of the actual form, and the range of variables is restricted. The light environment, wind environment, number of habitable households, design preference, and other factors are considered as the optimization objectives. Mutual constraints and contradictions exist among these elements. Algorithmic operations can balance multiple objectives to reach an optimal state, enabling the generation of the best form design through multidimensional consideration.

After different site environments are configured by using various simulation software, 18 groups of diverse building forms are established and their corresponding physical environments determined to obtain sufficient sample information, as shown in Figure 27. Then, the functional relationship between the building form index and the physical environment index is extracted.

FIGURE 27. Sample model.



(Figure source: self-drawn)

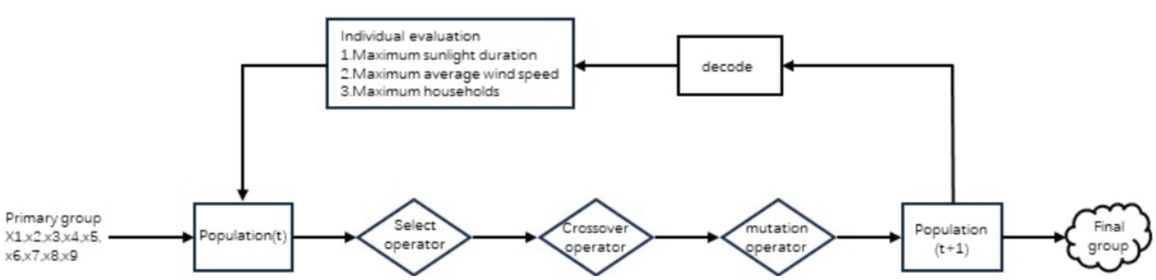
Based on the function formula, the goal of the analysis is to achieve a comprehensive optimal physical environment for the entire building, and the corresponding nearest form index is obtained to generate the corresponding design proposal.

2. MULTI-PLATFORM FITTING TOGETHER

In the process of a genetic algorithm solution, a single platform cannot meet the fitting requirements; therefore, multi-platform collaborative fitting is needed. Simultaneously, the calculation results of the light and wind environments were directly connected to the genetic algorithm for analysis. On the one hand, because a single simulation of the physical environment consumes much time, and the number of calculation rounds of the genetic algorithm is too large, the total operation time will be significant. However, directly importing existing wind environment simulation results into the optimization algorithm module is difficult, and platform disconnection is a problem. Therefore, the method of function fitting is considered to perform an approximate calculation; for example, a nonlinear function with a high goodness of fit is obtained using a machine learning algorithm. However, to further simplify the process and improve operational speed, a multiple linear fitting method was adopted to ascertain the relationship between the physical environment and design variables, as depicted in Figure 28.

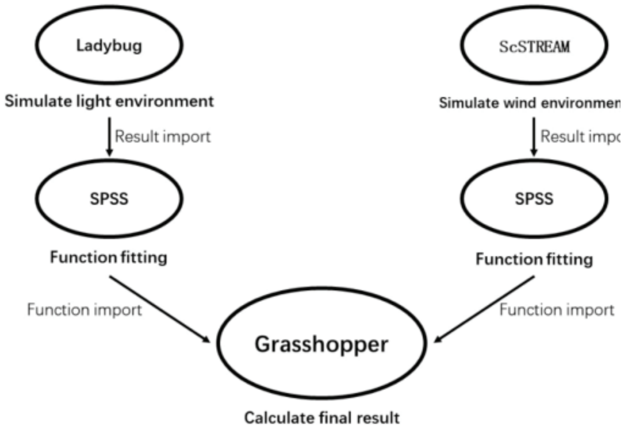
Based on the above analysis, a Grasshopper-Ladybug-ScSTREAM-SPSS collaborative workflow was adopted for the implementation process. The Galapagos battery in Grasshopper was used as the core arithmetic device to transform the multi-objective problem into a single-objective problem by performing weight coupling. Ladybug and ScSTREAM were used to determine the light and wind environments of the scheme, respectively. SPSS was used for the functional fitting.

FIGURE 28. Flowchart of the algorithm.



(Figure source: self-drawn)

FIGURE 29. Multi-platform collaborative logic.



(Figure source: self-drawn)

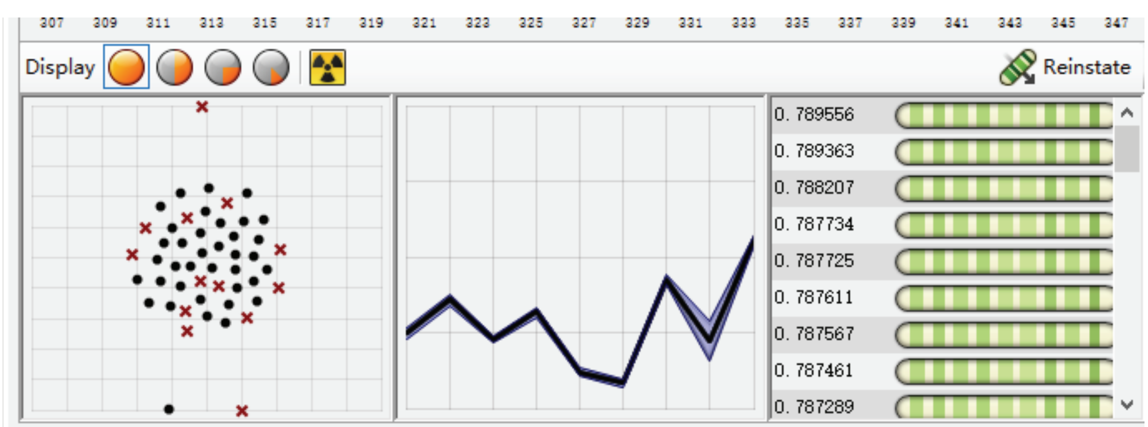
Finally, the specific values of each variable in the optimal solution state of the function were obtained through function calculation and analysis, as shown in Figure 30. An ideal architectural form is then obtained.

3.3.3 Summary

By exploring the building form that is most suitable for the site environment, we can reduce the energy loss caused by the physical environment during residential processes. Shi Hui Jie and Chai Kailin independently set shape-independent variables and optimization objectives with the help of algorithms and innovatively proposed the Grasshopper-Ladybug-ScSTREAM-SPSS collaborative workflow.

By simulating the sample model, the functional relationship between the independent variable and optimization target was obtained, thus significantly reducing the simulation analysis

FIGURE 30. Calculation result.



(Figure source: self-drawn)

time. To ensure the required calculation accuracy, an optimal solution under the requirements of multi-objective optimization is obtained more efficiently using a genetic algorithm. Through the optimization and improvement of the algorithm, a design idea that initially required a great deal of effort can be quickly and effectively practiced, and the work efficiency of the shape deliberation stage in the early stages of architectural design can be significantly improved.

However, this method only optimizes the entire building at the overall macro level, and the specific amount of carbon reduction that can be achieved needs to be further refined in design and calculation.

3.4 Compound optimization and utilization of radiant heat in the facade

Carbon emissions can be reduced in two ways: reduce energy consumption and capture more energy. Moreover, radiant heat on the opposite side can be handled in two ways: active and passive. The passive approach reduces energy consumption with the help of shading components to weaken the influence of solar radiation on the indoor temperature in summer. An active approach is to convert radiant heat into energy for a building using a photovoltaic (PV) system. The project had a plot ratio of 2.5 and a building density of 25%. Therefore, the roof area is relatively limited, and the building façade has a significant impact on the energy [14].

3.4.1 Progress in optimizing the use of radiant heat in facades

Sun shading has a significant effect on reducing the summer cooling energy consumption of buildings and improving indoor thermal comfort. The Yangtze River Delta exhibits distinct climatic characteristics. In summer, solar radiation entering the interior through windows is the leading cause of air conditioning energy consumption; therefore, window shading is significant [20].

The research on the application of PV modules in the field of building façades indicates that the module installation tilt and azimuth angle will have a certain impact on the power generation efficiency of the PV system under certain climatic conditions and a certain power generation efficiency of the PV cell [22]. The project was conducted in Nanjing, which is located in China, belonging to the Northern Hemisphere. Therefore, the PV panels should be placed as far as possible toward the south; the southeast or southwest angle can also be chosen. When the components faced south, the optimal tilt angle of the PV module was 32°, which was the same as that of the latitude [23]. When this component is not present, simulations are required to determine the optimal inclination angle [24]. Currently, the integration of PV and sunshades is the most applicable method for public rental housing. It can be independent of the building façade, form a self-contained system, and not have any influence on the original enclosure structure.

3.4.2 Optimizing design strategies

Tian et al. adopted an integrated design of PV modules and window-shading components to innovate the façade components to achieve multi-effective composites and respond to differences in the physical environment. The synergy of the integrated implementation is crucial to the design.

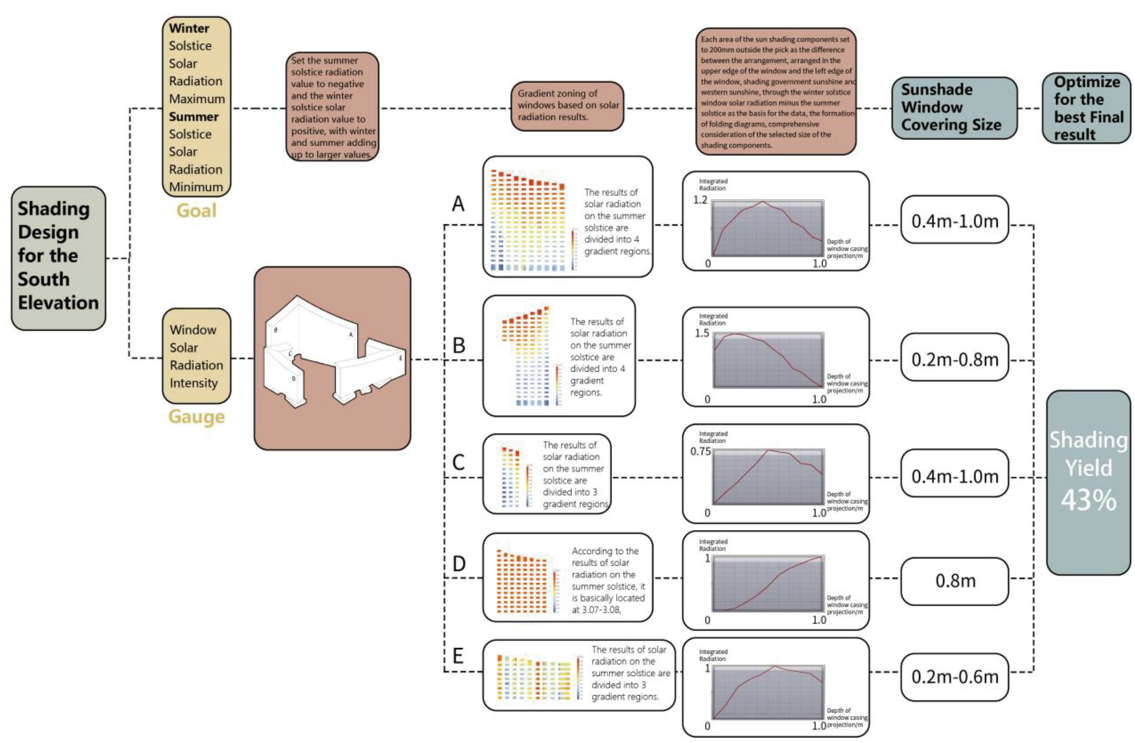
1) OPTIMIZED DESIGN OF WINDOW COVERINGS FOR SUN SHADING

The design adopts the "window cover" as the facade shading measures. The tilt angles of the window coverings on the top, bottom, left, and right sides are utilized to achieve the effects of controlling the midday solar radiation, collecting solar energy, blocking the western sunlight, and introducing the morning light, respectively. The design parameters of the window cover included the tilt angle in the four directions and the length of the projection.

First, determine the shading tilt angle of the “window cover.” According to Jie, tilted horizontal shading elements are more conducive for achieving shading in summer and gaining heat in winter. Its inclination angle ranged from 45° to 55° and did not vary with increasing latitude [29]. Thus, 45° was considered the horizontal shading inclination angle in this program. The vertical shading inclination angle of the west side was set to 45°, according to the purpose of shading the western sun and the effect of the facade. The inclination of the east side is naturally determined by the width of the wall between the windows, and a smaller inclination is favorable for the introduction of morning sunlight.

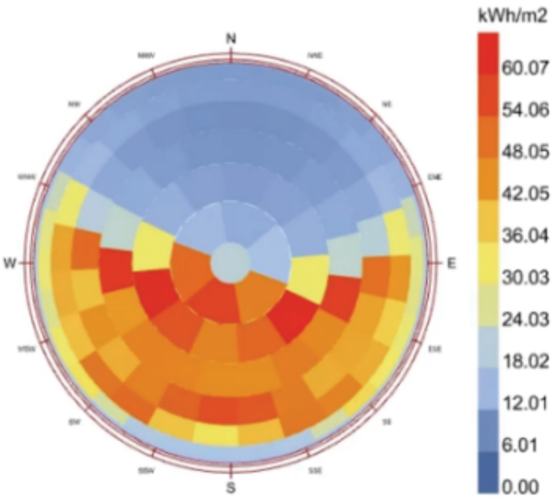
Secondly, the optimal pick length for the window casing must be determined. The optimal pick lengths of the sunshade components in different locations will differ owing to the different radiations and orientations. First, the façade was partitioned, and analysis by ladybug was applied to simulate and analyze the sunlight and radiation of the building façade without sunshade components. The façade is divided into three or four regions, from low to high, based on the solar radiation of the windows on the façade. The length of the sunshade plate pickup was set at the lowest radiation part of the facade (A_1) as the optimization variable. The lengths of the horizontal and vertical sunshade plate pickups were set in each region from low to high with a step value of 200 mm, and the effect of the window cover of the entire façade was controlled by adjusting A_1.

FIGURE 33. South elevation shading design flowchart.



(Figure source: self-drawn)

FIGURE 34. Nanjing's year-round solar sky model.



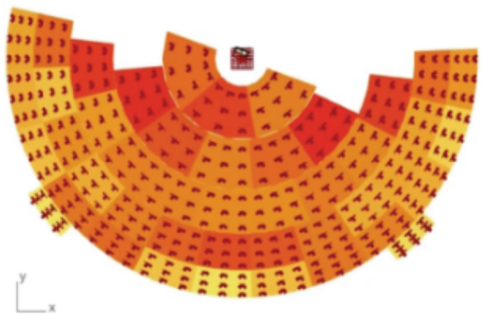
(Figure source: self-drawn)

Further, with reference to the simplified external shading coefficient formula given in the Energy Saving Design Standard for Public Buildings (GB 50185-2005),[1] the summer external shading coefficient (SDs[2]) measures the summer shading effect, and the winter external shading coefficient (SDw[3]) measures the winter shading effect. Based on Jie's study, (1-SDs)+SDw is used as the optimization objective to quantitatively analyze the comprehensive benefits of summer shading and winter lighting. The larger the value of this objective, the better the integrated effect of the window coverings [29]. The sunshade façade factor (PF) was taken as the horizontal axis, and (1-SDs)+SDw was considered as the vertical axis. The five south-facing elevations in the scheme were simulated, compared, and analyzed separately, and the folding diagrams shown in Figure 33 were formed.

In addition to the combined effects of shading, economics must also be considered. The more the window casing is projected, the higher the required cost. When the target value does not reach the peak value, as shown in Figure 35, an inflection point appears in the folding-line graph. That is, when the window set of picks increased by 200m (pick coefficient PF increased by 0.15) when the window set of picks was further increased, the increase in the target value slowed, and the optimization efficiency was low. At this time, instead of increasing the cost of

1. Horizontal visor: $SD_H = a_h PF^2 + b_h PF + 1$
Vertical visor: $SD_V = a_v PF^2 + b_v PF + 1$ Sunshade flare factor: $PF = A/B$
Where: SD_H—external shading coefficient of horizontal sunshade;
SD_V—external shading coefficient of vertical sunshade;
a_h ,b_h ,a_v ,b_v—calculation coefficients (check the table for values according to the standard);
PF—sunshade flare coefficient;
A—length of sunshade flare (m);
B—distance from the root of the sunshade to the opposite side of the window (m). [30]
2. Summer external shading coefficient: $SD_s = SD_H + SD_V$ (Calculate the coefficient according to the standard regulations to check the table to take the summer value)
3. Winter external shading coefficient: $SD_w = SD_H + SD_V$ (Calculation coefficients according to the standard regulations to check the table to take the winter value) [29]

FIG 35. Normal direction of the screened radiation sky model for each radiating surface).



(Figure source: self-drawn)

the pursuit of the peak value, choosing a program that has both an excellent comprehensive effect and economy is better.

In summary, simulation results show that the shade flare length on each façade is both beneficial overall and economically advantageous, calculating a total summer shading coefficient (SD_S) of 0.43 for the five south-facing facades, indicating a 43% shading gain.

2) WINDOW COVER PV MODULE DESIGN

In the arrangement of PV modules, the laying of PV panels on the roof surface is prioritized from the perspective of power generation efficiency, followed by the facade.

Because each south-facing facade is oriented at a different angle, the PV panels vary in inclination. The optimal inclination angle for each facade must be calculated. According to the sky model of the total annual insolation radiation in Nanjing (Figure 34), areas with higher yearly total radiation, that is, higher than 30kWh/m^2, were screened, and the orientation of each façade was determined (Figure 35).

Because the elevation direction and orientation of the PV panels are fixed, the azimuth with the maximum solar radiation needs to be sieved out to determine the optimal tilt angle of the PV panels. Based on the direction of the normal to the surface of solar radiation in the sky model, the angle of altitude, which is also the tilt angle of the PV panels, can be determined. The tilt angle of the PV panel determines the angle of the lower edge of the window cover, as listed in Table 1. The construction of the PV-shaded window cover is shown schematically in Figure 37.

TABLE 1. PV panel tilt angle for each south-facing elevation.

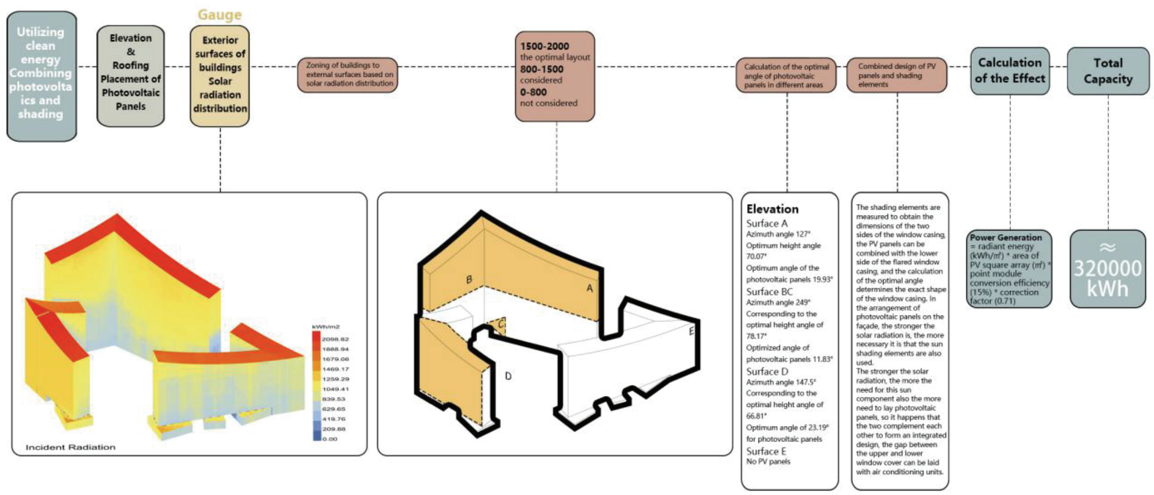
Orientation of the facade	Azimuth	Optimal altitude angle	Optimal angle
Elevation A	127°	70.07°	19.93°
Elevations B and C	249°	78.17°	11.83°
Elevation D	147.5°	66.81°	23.19°
Side E	Non-structured		

(Source of table: self-plotted)

Further discussion is required to determine whether PV modules are required for all window casings on a facade. According to the simulation results of solar radiation on the façade using Ladybug software throughout the year, the solar radiation is in the range of 0–2000 kWh/m². Accordingly, the facade was divided into three zones: 0–800, 800–1500, and 1500–2000. The optimal layout was 1500–2000; 800–1500 was considered, and 0–800 was not.

The flow of the facade PV module arrangement is shown in Figure 36. Finally, based on the formula power generation = radiant energy (kWh/m²) × area of PV square array (m²) × point module conversion efficiency (15%) × correction factor (0.71), the total power production is approximately 320,000 kWh/year, as measured by the effect of laying out PV panels on the façade and roof of the building.

FIGURE 36. PV Module arrangement flowchart



(Figure source: self-drawn).

FIGURE 37. Schematic construction of PV sunshade window coverings.

(Figure source: self-drawn)

3.4.3 Summary

To explore the comprehensive utilization of radiant heat on facades, we began with this mode: facade PV shading integration. We propose a specific operation plan based on simulation test analysis and result comparison. PV shading integration combines façade shading components with PV power generation to utilize solar energy resources efficiently, expand the power generation area and total power generation capacity, and realize the capacity of the public rental housing building itself. Many uncertainties remain in the actual project, and more variables will be present in the actual project that will affect the final result. Even in the built environment, the actual use effect will be lower than the theoretical value, but this is still an area worth exploring.

4. CONCLUSION

Carbon neutrality has become an important element of global climate action. In this context, building a healthy, livable and green living environment is the common goal of scholars in related fields. How to realize energy saving and emission reduction of buildings under the premise of meeting the needs of users has attracted the attention of many scholars, and in the field of architectural design, it encourages design practitioners to develop key skills that result in low-carbon buildings. For China, green low-carbon design education is a recent development, and related theoretical research and practical exploration are still very limited, therefore, this aspect is explored in this senior design course.

In this senior design course, the development of green and low-carbon rental housing is taken as the design topic, which essentially introduces the concept of "green" into the field of rental housing. To a certain extent, increasing the proportion of green low-carbon housing in the housing industry can greatly promote the development of China's low-carbon economy. To achieve the goal of green low-carbon, in addition to the selection of appropriate technology, equipment and materials, the planning and design of the building can also play a big role, which is exactly what this paper wants to explore through teaching practice.

By combining the actual situation of the project, analyzing and discovering the problems, and then mining the relevance of these problems and carbon reduction, and finding solution strategies from design thinking, the main results obtained include:

1. Green and low-carbon design should first uphold the concept of "human-centeredness" to inspire users to live in a greener, healthier and more sustainable way, and to contribute to the green transformation of society through individual and collective approaches. Therefore, in this design, first we emphasize the analysis of the behavioral patterns of the crowd, and carry out the space sharing design with a human-centered approach, so as to stimulate the green and low-carbon behavioral characteristics of the users and match them with the needs, thus reducing the energy consumption.
2. The green low-carbon design process should pay attention to the performance design, and in the teaching process, focusing on the development of core literacy of performance analysis. In this design teaching, students are encouraged to combine building performance simulation with design, breaking through the existing ventilation constraints of the central corridor building organization, and optimizing the wind and light environments of the residence in the design mode of "break up the whole into parts."
3. Green low-carbon design education emphasizes intersectionality and systemicity. On the one hand, it pays attention to the intervention of various tools such as model extrapolation, software analysis, algorithm optimization, etc., to assist the comprehensiveness

and systematicity of the analysis; on the other hand, it pays attention to the integration of cross-disciplinary knowledge such as energy, environment, economy, etc., to help students understand and analyze the challenges and problems of the green economy and sustainable development faced by buildings from different perspectives. For example, in this teaching, we try to use algorithmic optimization to improve the analysis efficiency and obtain better physical properties while making the building form generation more logical. Further, we combine the façade design with photovoltaic planning to strive for as much sunlight and light energy as possible.

These interesting attempts through design means can not only improve the physical environment within the form of the design results by developing knowledge, skills and attitudes and adapting to the needs of the green transition, but also make extensive use of clean energy, realize low-carbon environmental protection, respond to the current historical needs of carbon peak carbon neutral, and provide useful reference for the development of green and low-carbon design education in China.

ACKNOWLEDGEMENT

The authors would like acknowledge the National Natural Science Foundation of China (No. 52078112) for undertaking this research.

REFERENCES

[1] Zhang LX. Study on space design of long-term rental apartment under shared living mode—Take Chengdu as an example[D]. Sichuan:Southwest Jiaotong University,2020.
[2] Tian CL. Research on the Functional Configuration of Public Space for Centralized Long Rent Apartments—Taking Shanghai Area as an Example [D]. Chongqing:Chongqing University,2021.
[3] Development and Reform Commission Ministry of Finance of the People's Republic of China, Ministry of Natural Resources of the People's Republic of China. Ministry of Housing and Urban-Rural Development National Development and Reform Commission Ministry of Finance Ministry of Natural Resources:Opinions on further standardizing the development of public rental housing ([2019] No. 55) [EB/OL].
[4] http://www.mohurd.gov.cn/wjfb/201905/t20190517_240600.htm; (www.gov.cn)
[5] Chang MW,Yuan DC. Exploration of living space and living mode under the perspective of sharing economy[C]. Sustainable Development,Rational Planning—Proceedings of 2017 China Urban Planning Annual Conference (20 Housing Construction Planning), 2017.
[6] Hoelscher, M., et al., Quantifying cooling effects of facade greening: Shading, transpiration and insulation[J]. Energy and Buildings, 2016, 114: 283–290
[7] Castiglia Feitosa, R. and S.J. Wilkinson, Attenuating heat stress through green roof an green wall retrofit[J]. Building and Environment, 2018, 140: 11–22.
[8] Jan Gehl. Life between buildings using public space [M]. China Building Industry Press, 2002.
[9] Hu XJ, Cai LK, Ying XY. A Study of the Impact of Inner Courtyard Layout on Interior Wind Environment of Middle Flats of High-Rise Residential Buildings with Multiple Flats Sharing One Staircase [J]. Journal of Architecture, 2015(6):58–62.
[10] Cai LL. Optimized design of natural ventilation for intermediate units of high-rise residential buildings—an example of Suqian area [D]. China University of Mining and Technology,2021.
[11] Aflaki A, Mahyuddin N, Baharum M R. The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study[J]. Energy and Buildings, 2016, 126(13): 146–158.
[12] Deng X, Lai ZQ, Liang RZ. Analysis of solar irradiance of building photovoltaic systems[J]. China Building Metal Structure,2012(3):32–36.
[13] SHAO Q, WEI SC, XU YM, et al. Discussion on the effect of different shading measures in a high-rise residential building[J]. New Building Materials,2022,49(8):37–41,69.

[14] Ai SB,Wang J,Lu M. Dynamic distribution characteristics of solar radiation gained by buildings in different climate zones[J]. Building Energy Saving,2017(1):40–43,61.
[15] Cui YQ, Liu C, Chen B. Research and application of solar collector integration design methodology for green residential buildings—an example of a green residential district in Jinan City[J]. Building Energy Conservation,2021,49(3):49–55.
[16] Li XY, Characterization of carbon emissions from residents' living in high-density residential communities in Beijing [D]. Beijing: Beifang University of Technology,2022.
[17] Qi J. Research on the design of public rental housing units adapted to the living needs of young people [D]. Tsinghua University,2011.
[18] Duan Zhongcheng, Liu Zhengwei, CAI Leilei et al. Research on optimal design of natural ventilation in middle unit of high-rise residential buildings: A case study of Suqian District [J]. Construction techniques, 2022, 28(10): 101–107.
[19] Xie Yuntao. High-rise residential outdoor wind environment optimization design research [D]. Shandong construction university, 2022.
[20] Liu Zhe, Fu Xiuzhang, Yue Wenkun. Comparative study on the effect of different shading forms in Yangtze River Delta [J]. New Architecture, 2014, (04): 128–131.
[21] Shao Qi, Wei Shaochen, Xu Yanmei, et al. Study on the effect of different shading measures in a high-rise residential building [J]. New Building Materials 2022,49(8):37–41,69.
[22] Bian Mengmeng, Zhang Xinyu, Yin Chong et al. Research status of application technology of photovoltaic modules for building facades [J]. Building Science, 2019,36(06):127–135. (in Chinese)
[23] Jovanovic Jovana, Sun Xiaoqin, Stevovic Svetlana, et al. Energy-efficiency gain by combination of PV modules and Trombe wall in the low-energy building design [J]. Energy and Buildings, 2017, 152:568–576.
[24] Yang Jinhuan, Mao Jiajun, Chen Zhonghua. Calculation of solar radiation and optimal tilt angle on inclined planes with different orientations. Journal of Shanghai Jiao Tong University, 2002, 36 (7).
[25] Yu Q. Building Facade Design Study of BIPV [D]. Zhejiang University of Technology,2014.
[26] Zhao Z. Integrated Design of Photovoltaic System of Building Facade in Hot Summer and Cold Winter Region [D]. Nanchang University,2014.
[27] Wang J. Research on BIPV Application Potential in Urban Residential in Tianjin [D]. Tianjin University, 2012.
[28] Ma J. Analysis of light transmittance of window shading structures in Guangzhou [D], Guangzhou; South China University of Technology, 2003.
[29] Shen J. Research on Methods of Using Technical Analysis in Grasshopper for Green building Design [D]. South China University of Technology,2012.
[30] Ministry of Construction of the People's Republic of China. Energy saving design standard for public buildings GB50189–2005 [S]. Beijing;Ministry of Construction of the People's Republic of China.2005