Research on The Improvement Effect of Human Factor Quality After Energy-Saving Renovation of An Office Building in Shanghai

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ABSTRACT

Green and low-carbon development has been the development direction of the construction industry in recent years. The total energy consumption of building operation is substantial, accounting for a high proportion of overall energy consumption, and energy-saving renovation of existing buildings is a key measure to enhance building sustainability. Furthermore, with the robust development of China's economy, the traditional development model driven by capital and labor has been gradually replaced by the people-oriented development concept. The specific manifestation of this macro social background in the construction sector is the growing emphasis on the physical and mental health of building users. With the improvement of public living standards, healthy, comfortable and high-efficiency human experience has gradually become a critical indicator for evaluating the quality of built environments. This paper is based on the renovation project of the 7th floor of an office building in the Xuhui Campus of Shanghai Academy of Building Research, takes the renovation measures of this office building as the research focus, introduces and analyzes the renovation measures of the office building from the perspectives of luminous environment and wind environment respectively, focuses on the construction cost during renovation and the energy-saving effect after renovation, and prioritizes the research on the improvement effect of human factor quality after renovation. The main research methods adopted in this study are as follows: the luminous environment indicators of the office building are simulated through the Ecotect software, the wind environment indicators are analyzed via the Vento software to obtain the output of Predicted Mean Vote (PMV) values, and then the improvement effect of human factor quality after renovation is investigated in combination with relevant references. The luminous environment section mainly investigates the natural daylighting performance of the office building, while the wind environment section mainly analyzes the overall natural ventilation performance before and after renovation, as well as the thermal comfort under different working conditions before and after renovation. Starting from human living experience and anthropometric characteristics, and based on modern human factors engineering, human factor quality focuses on the interaction between human beings and urban spaces at all scales. It guides the construction of new spaces, the renovation of existing spaces and the management of public facilities through systematic scientific methods, aiming to effectively improve the aesthetic perception and well-being of urban life. The core connotation of human factor quality is the comprehensive capability of the built environment to meet the needs of users at the physiological, psychological and behavioral levels. Accordingly, this paper analyzes the improvement effect of human factor quality brought by the renovation scheme from multiple dimensions including physiology, psychology and behavior.

Key words: Energy-saving renovation, human-centric quality, simulation, light environment, wind environment

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1 Introduce Assertion

1.1 National Background of Building Energy Consumption

1.1.1 The background of building energy consumption in China

The construction industry constitutes one of the major sectors of energy consumption and carbon emission in China. The *Work Plan for Accelerating Energy Conservation and Carbon Reduction in the Construction Industry*, jointly issued by the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development, clarifies that advancing energy conservation and carbon reduction in buildings is of great significance for realizing carbon peaking and carbon neutrality goals as well as high-quality economic development [1]. Domestic and foreign scholars have carried out extensive research on building energy consumption in recent years, forming a systematic theoretical framework.

1.1.2 High Total Volume and Proportion of Building Energy Consumption

In terms of total energy consumption, the scale of China's building energy use remains substantial. Citing the *Annual Research Report on China Building Energy Efficiency (2024)*, Professor Zhu Yingxin pointed out that China's annual building energy consumption rose from 625 million tons of standard coal in 2010 to 1.12 billion tons of standard coal in 2022, representing a remarkable growth over twelve years [2]. In terms of carbon emission proportion, building carbon emissions account for approximately 32% of China's total social carbon emissions [2]. Calculations released by the International Energy Agency (IEA) in 2023 show that construction and building operation consume 34% of global total energy, among which building operation accounts for 30% [2]. This indicates that the building sector acts as a critical carbon emission source at both domestic and global scales.

The Research Report on Carbon Emissions in China's Urban and Rural Construction Sector (2025)*, published by the China Association of Building Energy Efficiency, further presents quantified data: in 2024, the energy consumption of China's civil buildings reached 1.3 billion tons of standard coal, accounting for 21.8% of national total energy consumption; the corresponding carbon emissions hit 2.47 billion tons of CO_2, making up

22.1% of national energy-related carbon emissions [3]. The energy consumption of public buildings accounts for roughly one-third of total building operation energy consumption, with an upward trend alongside socioeconomic expansion.

1.1.3 Large Stock and Low Energy-Saving Level of Existing Buildings

While attention is paid to newly constructed buildings, the massive stock and poor energy performance of existing buildings form a critical structural factor driving high energy consumption. Relevant studies confirm that most existing buildings in China feature weak thermal insulation of building envelopes, classifying them as high-energy-consuming structures [4]. Literature has identified prominent bottlenecks restricting green low-carbon development of buildings, including excessive energy use of partial new constructions and the large volume of existing buildings with retrofitting barriers [5].

In terms of stock scale, the total floor area of urban existing public buildings exceeded 16 billion square meters by 2023, including a considerable share of non-energy-efficient buildings with high unit-area energy consumption and carbon emission intensity [6]. According to the *14th Five-Year Plan for Building Energy Efficiency and Green Building Development* issued by the Ministry of Housing and Urban-Rural Development, over 350 million square meters of existing buildings (including 250 million square meters of public buildings) shall complete energy-saving renovation by 2025 [6]. The massive retrofitting target fully reflects the severe underperformance of existing building stock.

1.1.4 Heating and Air-Conditioning as Dominant Energy Consumption Sources in Building Operation

Heating and air-conditioning systems dominate energy consumption within building operation. Poor thermal insulation performance of building envelopes leads to high heating and cooling loads across China’s diverse climate zones: severe cold and cold zones face massive heating demands, while hot summer and warm winter zones require intensive cooling, forming dual energy consumption pressures.

Power consumption contributes 66.8% of building operation carbon emissions, with fossil fuel and thermal energy each accounting for 16.6% [3]. The high proportion of electricity consumption highlights cooling, heating and lighting equipment as primary carbon emission contributors. Even industrial buildings exhibit similar characteristics: cooling and chiller systems consume over 60% of total electricity for lithium battery production plants [2], further verifying the dominant energy consumption status of HVAC systems.

1.1.5 Severe Energy Conservation and Carbon Reduction Challenges Faced by the Construction Industry

Synthesizing the above analysis, the construction industry faces multiple structural barriers to energy conservation and carbon reduction, including excessive energy use of partial new buildings, massive existing building stock with high retrofitting difficulty, insufficient operational energy management mechanisms, and inadequate technical and policy support for low-carbon transformation [5]. The State Council has mandated a sound institutional framework for building energy conservation and carbon reduction by 2025, with full implementation of green building standards for all new urban constructions [1]. Nevertheless, existing public building retrofits are hindered by high upfront investment and long payback periods. Although envelope and HVAC retrofits deliver nearly 80% of total energy savings, high technical costs limit large-scale implementation without effective incentive policies [6].

1.2 Research Background from the Human Factor Perspective

1.2.1 People-Oriented Ideology Driving the Upgrade of Built Environment Quality

As China's economy enters a new normal, capital- and labor-driven growth models are gradually replaced by people-oriented development philosophies [7]. This macro trend translates to the construction industry through growing public focus on occupants' physical and mental well-being. The prevalence of electronic devices has drastically elevated the incidence of myopia, projected to exceed 700 million nationwide, making office luminous environments a key public concern [8]. Meanwhile, public awareness of indoor air quality has risen sharply amid outdoor air pollution and indoor decoration contamination incidents [9]. Building environment evaluation has transcended basic functional standards to prioritize high-level demands for health and comfort.

1.2.2 National Top-Level Design Providing Impetus for Human Factor Research

National strategic frameworks create robust policy drivers for human factor research in buildings. The *Healthy China 2030 Outline* and dual carbon goals mandate low-carbon construction while safeguarding occupants' physical and mental health, prohibiting excessive energy consumption at the cost of human well-being [9]. National safety development strategies emphasizing “life first” further reinforce the value of human-centric design [7]. Collectively, these national policies form the core social driving force for human factors engineering applications in built environment research.

1.2.3 Limitnal Paradigms in Meeting Refined Demands

Despite clear policy guidance and market demand, conventional research and design frameworks fail to satisfy refined human-centric requirements. In luminous environment design, although national standards stipulate minimum illuminance thresholds, actual offices suffer from uneven lighting and glare, creating a notable gap between code compliance and subjective comfort [8]. In construction safety management, regulatory and technical interventions dominate while psychological and cognitive mechanisms of unsafe behaviors are overlooked, leading to persistent safety risks [7]. Traditional methodologies over-rely on physical parameter measurements and external behavioral observation, lacking in-depth exploration of occupants’ subjective perception and physiological mechanisms, forming theoretical bottlenecks [7-9].

1.3 Building Overview

1.3.1 Basic Building Information

The renovation project is located in the Xuhui District of Shanghai, on the 7th floor of a building approximately 20 meters above ground level.

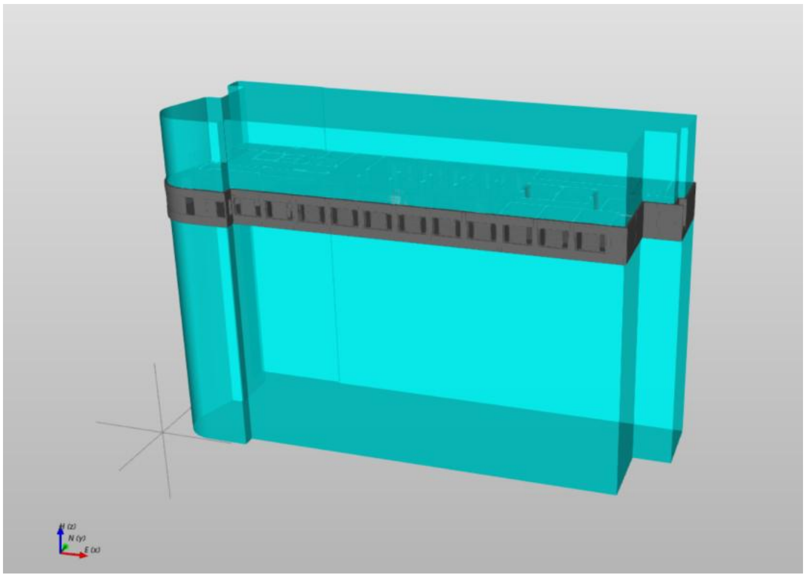

Figure 1.1 Schematic diagram of the floor layout of the office building

The total construction area of the target floor reaches 757 m², with a usable area of

680 m². The original layout adopted a central corridor typology, consisting of isolated small offices and a large conference room at the corridor terminus.

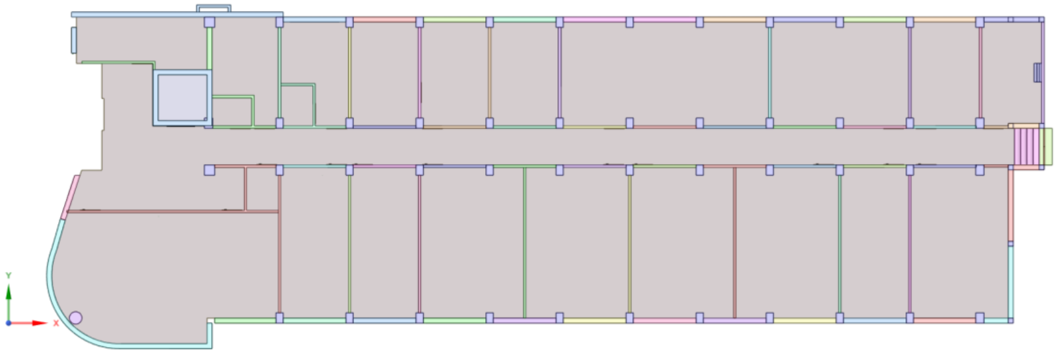

Figure 1.2 Schematic diagram of the original central corridor layout before renovation

This layout suffers multiple drawbacks from diverse evaluation dimensions:

Collaboration: Segmented small rooms hinder cross-team communication, failing to accommodate growing business interaction demands.

Luminous environment: The enclosed central corridor requires permanent artificial lighting; low ceilings and partition screens severely restrict natural daylight penetration, raising lighting loads and reducing visual comfort.

Wind environment: Single-sided windows eliminate cross-ventilation airflow, resulting in poor natural ventilation and increased air-conditioning runtime.

Occupational well-being: No dedicated leisure or rest zones are provided, negatively impacting staff physical and mental health.

The above limitations demonstrate strong necessity for comprehensive renovation, with detailed luminous and wind environment retrofitting measures elaborated below.

1.3.2 Luminous Environment Renovation Measures

As shown in Figure 1.3, the renovated office building adopts an open-plan layout, omitting some partition walls and suspended ceilings while retaining the original terrazzo flooring. These measures have, to a certain extent, reduced construction costs.

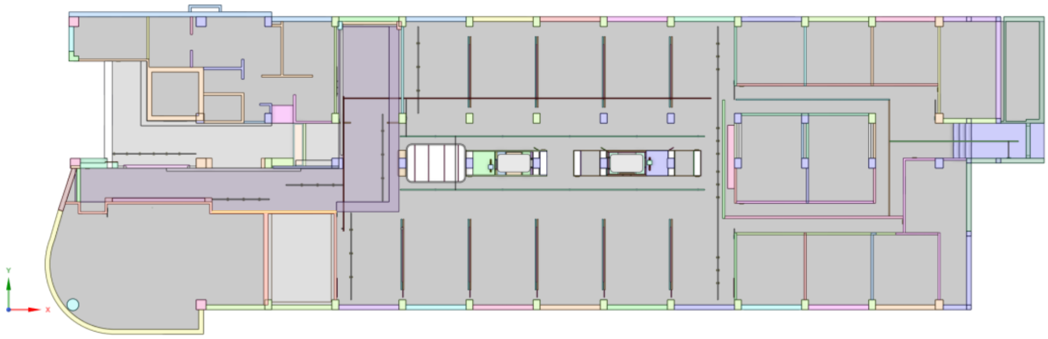

Figure 1.3 Overall layout after renovation

The open-plan layout significantly enhances the building's utilization of natural daylight. The ceiling-free design expands the interior space, providing office workers with a broader field of view.

Figure 1.4 Schematic diagram of the ceiling-free design

After the renovation, most walls and ceilings are painted white, and white panel furniture has been selected. This allows natural light to reach deeper into the interior through diffuse reflection from the walls and furniture.

Figure 1.5 Schematic diagram of white walls and white furniture

To achieve better shading, the renovated building uses venetian blinds, which effectively introduce and regulate natural light. They can block glare while reflecting light into the interior to illuminate the ceiling. Moreover, the slat angle can be adjusted according to individual preferences and needs, aligning with the fundamental principles of ergonomics.

Figure 1.6 Schematic diagram of venetian blinds

The renovated building employs a zone-controlled lighting method. The two linear LED lights above each workstation row in the office area can be controlled separately, allowing the number of switched-on lights to be adjusted based on natural light duration. The grid lights in the meeting room are divided into three control zones, enabling the selection of lighting coverage based on different usage needs. This shows that the flexibility of use has been greatly enhanced after the renovation.

Figure 1.7 Schematic diagram of zone-controlled energy-saving light fixtures

1.3.3 Wind Environment Renovation Measures

As mentioned earlier, after the renovation, the office building adopts an open-plan spatial layout. From the perspective of optimizing the building's wind environment, the transparent and spacious open-plan structure effectively reduces the obstruction and fragmentation of airflow caused by wall partitions, significantly improving indoor air circulation efficiency. This fully leverages the advantages of natural ventilation and improves overall ventilation conditions. Improved natural ventilation not only reduces the usage time and frequency of air conditioning, achieving energy saving and emission reduction, but also better aligns with ergonomics, providing users with a more comfortable office experience.

A centralized communication area is set up in the middle of the open-plan space, uniformly furnished with low-height furniture and lightweight partitions to prevent tall furniture from obstructing airflow paths. This preserves and maintains the transparent north-south flow line indoors to the greatest extent, ensuring the smooth passage of cross-ventilation.

The large meeting room on the southwest side is a key functional space. During the design phase, the site’s wind characteristics and spatial usage were fully considered. Operable exterior windows were installed on two sides of the room to create a bidirectional convection ventilation layout, forming a stable double-sided ventilation system. This effectively accelerates the indoor air exchange rate, resulting in significant natural ventilation effectiveness, which can effectively address peak instantaneous heat and moisture loads and the respiratory safety concerns caused by high occupant density.

Figure 1.8 Schematic diagram of the large meeting room

For small independent offices within the building, due to the compact spatial scale, limited personnel activity range, and relatively small space load, single-side operable exterior windows alone can meet the daily air exchange and ventilation requirements. This balances spatial functionality with ventilation comfort.

Figure 1.9 Schematic diagram of a small office

1.3.4 Other Renovation Measures

After renovation, the office building has added small discussion areas, phone booths, and a fitness area. The small discussion areas are special zones that fall in nature between workstations and meeting rooms. They solve the problem of inconvenient communication at workstations, which easily disturbs others, while also removing the ceremonial burden of entering a meeting room. Research suggests that many crucial communications occur during unplanned, brief interactions. At the same time, unlike the quiet atmosphere of workstations, small discussion areas offer staff brief moments of respite during breaks.

The open-plan office space brings many advantages, such as improved natural lighting and ventilation, significant energy savings, and increased communication efficiency. However, it inevitably increases the potential for staff to be disturbed by the surrounding environment. The phone booth is a highly sound-absorbent, strongly isolating micro-cabin that provides a space for long, confidential, or highly focused calls. The introduction of phone booths achieves a dynamic balance between social connection and acoustic privacy, reflecting the human-centric design of the renovation plan.

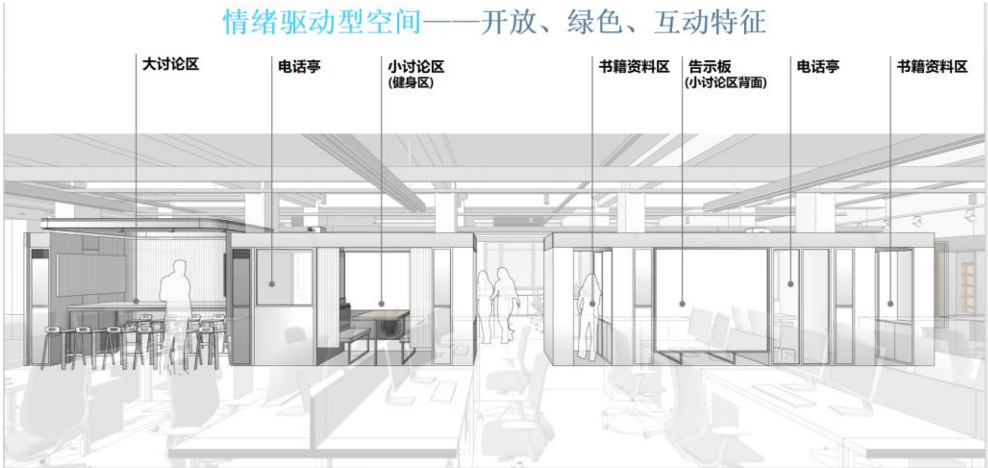

Figure 1.10 Emotion-driven space design

The fitness area in the office building is not intended to replace a professional gym but rather serves as activity and stretching points set along daily work routes. Prolonged sedentary work can easily cause musculoskeletal issues in the cervical and lumbar spine, as well as psychological fatigue, which have become major occupational health risks. Arranging areas for stretching, light aerobics, or simple strength training in the workplace holds significance beyond traditional welfare. From a physiological perspective, it interrupts prolonged sitting, helps improve local blood circulation, and engages different muscle groups. From a psychological perspective, brief physical activity can alleviate sustained mental stress, making it easier for staff to concentrate on subsequent tasks. Furthermore, a shared fitness space allows everyone to be active together in a non-competitive atmosphere, subtly enhancing support and a sense of belonging among colleagues. Compared to going to an external gym, an on-site fitness area saves travel time and hassle, making healthy activities a more natural choice rather than an extra burden.

1.4 Significance of the Building Renovation

1.4.1 Energy Saving

From a macro perspective, in the current social context, the energy-saving renovation of existing buildings represents a convergence of multiple values, including national strategy, urban development, and people’s well-being. Buildings are one of the three major energy-consuming sectors. In 2021, building operation energy consumption accounted for 30% of global energy consumption, and building operation-related carbon emissions accounted for 27% of global carbon emissions (including energy and industrial process greenhouse gas emissions)[10]. In terms of carbon emission proportion, China's building carbon emissions account for approximately 32% of the total societal carbon emissions[2]. The International Energy Agency's 2023 assessment also shows that global energy use related to building operations and construction accounts for 34% of total global energy consumption, of which 30% is attributed to building operations[2].

Energy-saving renovation of existing buildings can reduce electricity loads for heating, air conditioning, and lighting, making it a rapid and high-potential carbon reduction pathway. Reducing electricity loads can effectively alleviate peak grid pressure, decrease reliance on fossil fuels, enhance energy self-sufficiency, and thus safeguard national energy security.

Energy-saving renovation is a crucial part of upgrading old buildings and improving urban quality, making cities greener and more livable. China has a massive stock of existing buildings, many of which were built earlier and suffer from high energy consumption, low energy efficiency, and outdated functions. This not only exacerbates energy resource pressure but also contradicts the concept of green economic development. In this context, promoting the energy-saving renovation of existing buildings is no longer just a technical upgrade project but also a vital measure to practice green economy principles and implement the national carbon peak and carbon neutrality strategy[11].

Meanwhile, energy-saving renovation involves an entire industrial chain including insulation materials, energy-saving windows and doors, building-integrated photovoltaics, heat pumps, intelligent control systems, and renovation construction. It can stabilize investment while driving the transformation of traditional buildings towards green, industrialized, and intelligent practices.

For the specific office building in this study, the central corridor layout made the corridor dim, requiring year-round artificial lighting. The low suspended ceiling and screen obstructions resulted in low utilization of natural daylight, increasing the lighting load. The central corridor layout also meant each room had windows on only one side, resulting in poor natural ventilation and thereby increasing the air conditioning load. Therefore, energy-saving renovation of this office building is highly necessary.

Regarding the luminous environment, the original traditional central corridor layout had significant environmental shortcomings and energy consumption defects. The long, narrow, enclosed central corridor lacked direct exterior windows, resulting in poor overall lighting conditions and a generally dim environment, necessitating long-term reliance on artificial lighting during office hours, with lights operating for long periods at high frequency. Furthermore, the low suspended ceiling design and numerous partition screens further hindered the penetration and diffusion of natural light, greatly weakening the building's ability to utilize natural daylight resources, leading to wasted daylighting energy and a significantly increased overall lighting energy load.

Regarding the wind environment, the central corridor layout allowed for windows on only one side of the offices on both sides, preventing the formation of effective air convection and cross-ventilation. This hindered indoor air circulation and resulted in insufficient air exchange efficiency, with very limited overall natural ventilation. To compensate for poor ventilation and indoor stuffiness, the building had to rely long-term on air conditioning equipment to regulate indoor temperature and humidity, thereby continuously increasing the air conditioning system's operating energy consumption.

Overall, the insufficient daylighting and poor ventilation caused by the original spatial layout collectively resulted in high building energy consumption and inadequate spatial comfort. Therefore, scientifically sound energy-saving renovation to optimize spatial layout, improve natural daylighting and ventilation conditions, reduce building lighting and air conditioning energy consumption, and enhance overall indoor environmental quality holds strong necessity and practical significance for this office building.

1.4.2 Human Factors Quality Improvement

In recent years, urban construction projects have achieved high-quality assurance in terms of scale, facility configuration, and functional planning. However, regarding the interface of interaction between the environment and people in daily life, poor spatial quality remains a common phenomenon in contemporary cities. Against this backdrop, urban ergonomics has emerged. Starting from human living experiences and bodily characteristics, based on contemporary human factors technology, it focuses on the interaction between urban spaces and people at various scales. Using systematic scientific methods, it guides the creation of new spaces, the renovation of existing spaces, and the management of public facilities, aiming to effectively enhance the sense of beauty and well-being in urban life[12].

Ergonomics/human factors is dedicated to analyzing and applying human factors in the interaction process of the human-machine-environment system. By designing systems, it makes the interaction between the system/environment and humans more effective, safer, healthier, and more comfortable, leading to greater user satisfaction and ultimately enhancing social well-being and equity. The essence of human factors quality centers on human needs, relies on ergonomics theories, and considers users' physiological, psychological, behavioral, and diverse humanistic needs. Human factors design covers physical conditions such as indoor thermal comfort, acoustic and luminous environments, and air quality, while also integrating spatial circulation, functional layout, and accessible design to optimize the building space user experience. Human factors quality can balance low-carbon energy saving with living experience, driving the built environment towards a healthy, comfortable, and efficient high-quality direction. Therefore, modern building renovation demands not only energy saving but also attention to the effectiveness of human factors quality improvement.

1.5 Main Tools and Methods Used in This Study

1.5.1 Luminous Environment Analysis Tools and Methods

The luminous environment analysis requires simulating the building's overall natural daylighting. Based on the evaluation indicators for indoor luminous environment parameters specified in the "Assessment Standard for Green Building" GB/T 50378-2019, Ecotect combined with Radiance is used for co-simulation of relevant environmental parameters before and after renovation. The luminous environment indicators are then compared, and the corresponding lighting energy savings are ultimately calculated.

1.5.2 Wind Environment Analysis Tools and Methods

The wind environment analysis requires simulating the building's overall natural ventilation. Evaluation is based on the thermal comfort index PMV. Vento is used for Computational Fluid Dynamics (CFD) simulation of natural ventilation during transition seasons. The PMV values of the rooms after renovation are then outputted, and the conditions falling within the ±1 range are counted to determine whether air conditioning needs to be activated, thereby deriving the reduction in HVAC energy consumption.

2 Luminous Environment Analysis

2.1 Luminous Environment Renovation Methods

The luminous environment renovation methods have been introduced in the introduction section and can be summarized as follows:

Before renovation, the central corridor layout resulted in poor daylighting in the corridor area, requiring year-round artificial lighting. After renovation, an "open-plan + small room" layout was adopted, and the open-plan area removed suspended ceilings and partition walls, greatly improving the utilization of natural daylight in the indoor space.

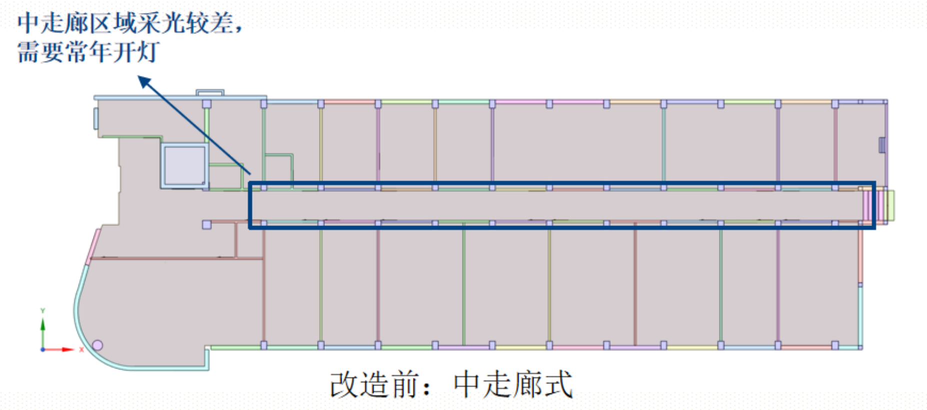

Figure 2.1 Schematic diagram of the pre-renovation central corridor layout

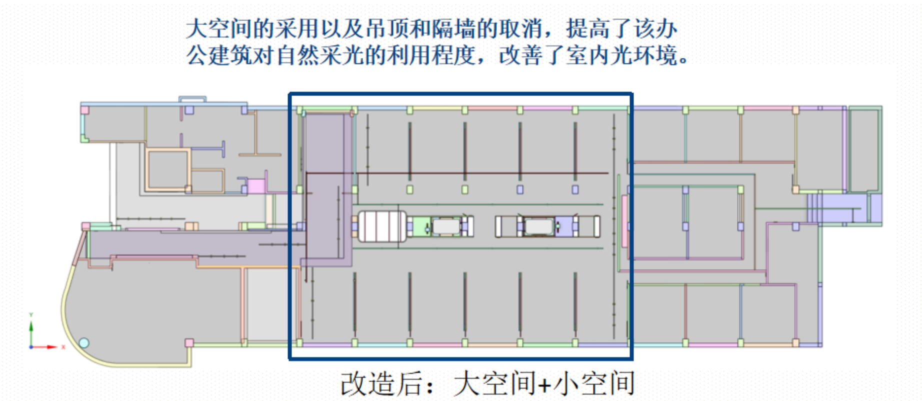

Figure 2.2 Schematic diagram of the post-renovation "open-plan + small room" layout

Furniture finishes uniformly adopt light-colored surfaces, which are more conducive to indoor light diffuse reflection. The reflectance of light-colored surfaces is much higher than that of dark surfaces, capable of reflecting most incident light back into the room, rather than absorbing large amounts of light energy like dark furniture, which causes spaces to appear dim. At the same time, common wood or matte finishes inherently possess fine textures and are not mirror-like, scattering light uniformly throughout the space during reflection. Thus, unified and bright light tones avoid high contrast between local darkness and brightness, making the entire room's luminous environment uniform and soft, enhancing visual comfort, indirectly improving the utilization efficiency of both natural and artificial lighting, and making the interior appear brighter.

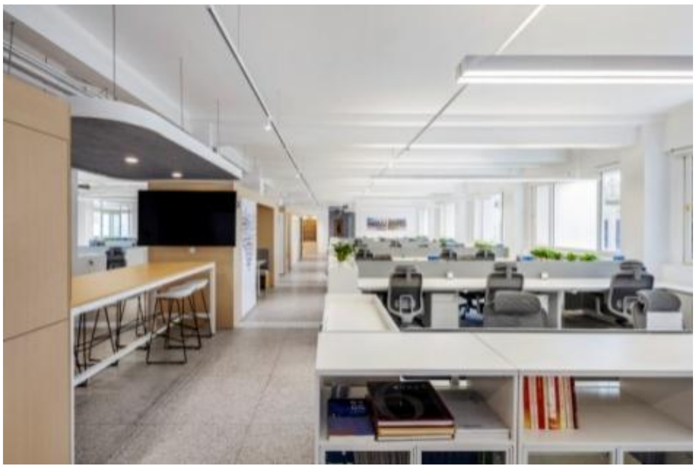

Figure 2.3 Schematic diagram of interior finish colors

Where partitions are necessary, transparent glass partitions are uniformly used to reduce obstruction of light propagation, thereby improving the building's utilization of natural daylight.

Figure 2.4 Schematic diagram of transparent interior partitions

To meet shading requirements at specific times, the office building uses light-directing venetian blinds, which can reflect light into the interior to illuminate the ceiling. The slats of the blinds can be adjusted at multiple angles, flexibly utilizing natural light while effectively avoiding glare.

Figure 2.5 Schematic diagram of light-directing venetian blinds

2.2 Luminous Environment Analysis Tools

The luminous environment analysis tool used in this study is Ecotect Analysis. Ecotect Analysis is a comprehensive computer simulation software developed by Autodesk for analyzing important building environments such as thermal, luminous, and acoustic environments. It is mainly applied in architectural design, urban planning, building environment education, and green building research. In high-rise building design and ordinary residential construction, Ecotect is widely used for auxiliary analysis of comprehensive building performance[13]. Ecotect incorporates Radiance output and control functions, greatly expanding its application scope and providing users with more options. Ecotect is suitable for architects and planners during the early and middle stages of building design to compare schemes through computer simulation, optimizing and improving the building design scheme, thereby avoiding the embarrassment of design changes in later stages. It helps building designers introduce ecological and energy-saving concepts early in the design process to achieve comfortable and energy-efficient building scheme designs.

Within the scope of this research project, the selected office building has already completed its energy-saving renovation, and its actual post-renovation usage status and spatial environmental conditions are stable. Therefore, this study does not need to participate in renovation design or construction stages; it focuses solely on the environmental and energy consumption parameters of the building before and after renovation, comparatively analyzing the numerical changes and characteristic differences of key indicators. Through quantitative data comparison and environmental simulation results, the actual optimization effects brought by the renovation scheme are intuitively sorted out, allowing for an in-depth understanding of the design ideas and overall considerations of the architects in the early stages of scheme planning, energy-saving strategy selection, and spatial environment optimization. It also enables a clear recognition of the core logic and practical key points of existing building renovation design, thereby completing the theoretical inquiry and case analysis of the research topic, ultimately achieving the core goals of professional knowledge accumulation, design thinking expansion, and research learning.

As a professional building environment simulation software, Ecotect possesses comprehensive and diverse simulation calculation functions suitable for multi-dimensional simulation studies on building luminous environments, thermal environments, and comfort performance. Its core application functions include: simulation analysis of temperature fields and spatial temperature distribution inside and outside buildings, quantitative assessment of thermal comfort indices for the whole building and partial spaces, calculation and analysis of daylight illuminance and uniformity under different time periods and conditions, as well as specific studies on building energy consumption simulation, solar radiation analysis, shading effect assessment, etc. It can provide scientific and intuitive data support and visual analysis results for comparative studies of environmental performance before and after existing building renovations, greatly enhancing the professionalism and scientific nature of the research project.

2.3 Luminous Environment Simulation Process

2.3.1 Indicator Requirements

The "Assessment Standard for Green Building" GB/T 50378-2019 proposes the following evaluation indicator for indoor luminous environment: compliance is considered achieved when the area proportion where the average hours of daylight illuminance meeting requirements in main functional rooms is no less than 4 h/d reaches 60%. The standard values for Class III daylight illuminance and Class III daylight factor for public buildings are shown in the table below (the conditions studied in this project pertain to side daylighting)[14].

Table 2.1 Standard values of daylight illuminance and daylight factor for public buildings

Side daylighting	
Daylight factor standard value (%)	Daylight illuminance standard value (lx)
3.0	450.0

2.3.2 Simulation Overview

The 2019 revision of the "Assessment Standard for Green Building" introduced a dynamic analysis method: the dynamic daylighting evaluation method, which is adopted in this project for daylighting analysis. For the calculation of daylight factor, a time-by-time, point-by-point illuminance simulation method is used. Specifically, the horizontal plane at a height of 0.75 meters from the floor of the civil building model is divided into multiple grids with a certain accuracy. Basic condition parameters affecting daylighting, such as interior materials and external obstructing buildings, are set. By invoking the US Radiance calculation kernel, illuminance calculations are performed for each grid at 1-hour intervals.

2.3.3 Model Building and Processing

（1）Three-dimensional models of the office building before and after renovation were created in SketchUp. The pre-renovation model is shown in Figure 2.6, and the post-renovation model is shown in Figure 2.7.

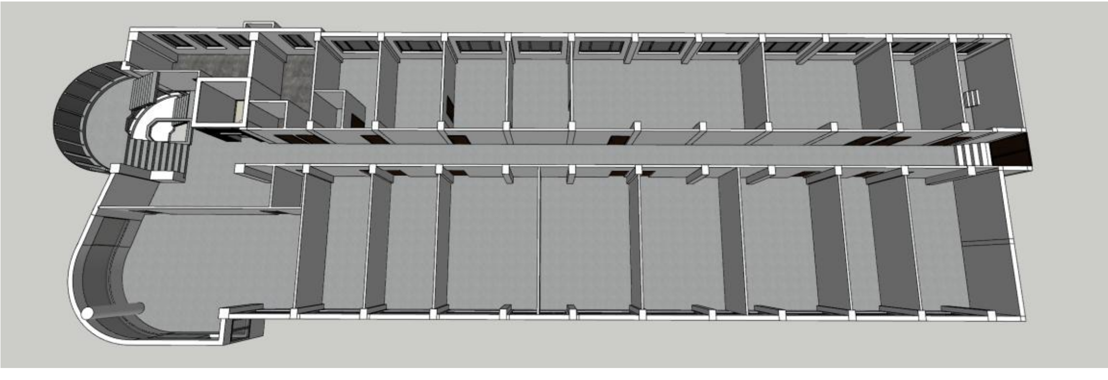

Figure 2.6 Pre-renovation model in SketchUp

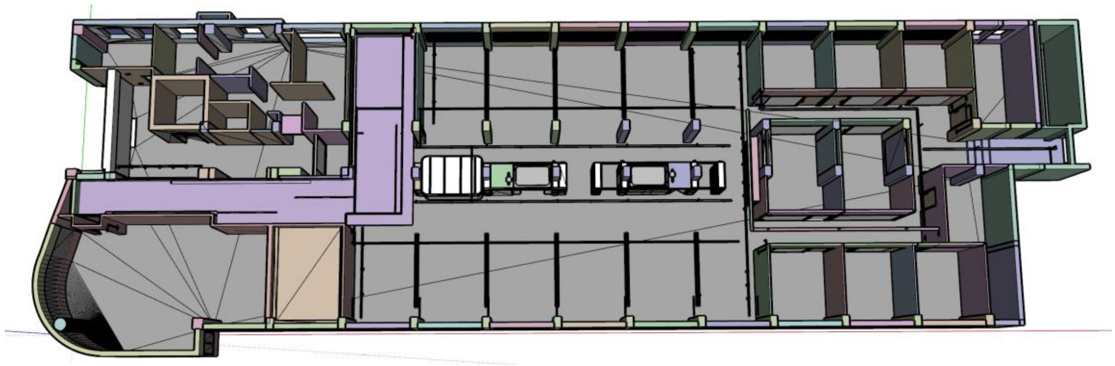

Figure 2.7 Post-renovation model in SketchUp

（2）After modeling, the 3D models were exported in dxf format for use in Ecotect.

（3）The 3D models were imported into Ecotect, and the materials for each zone of the model were set.

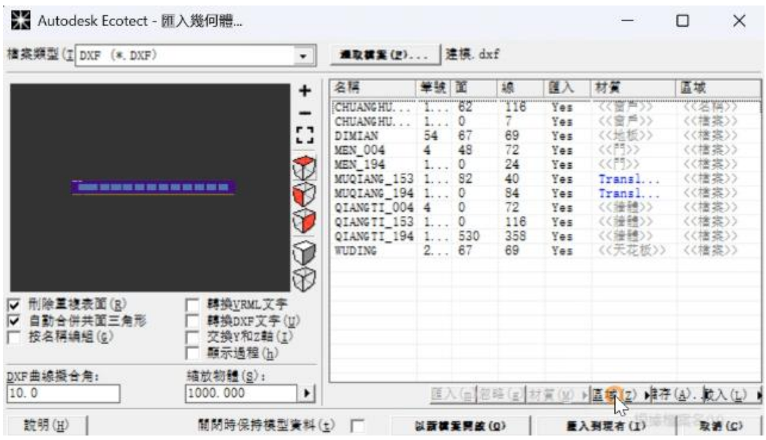

Figure 2.8 Material settings interface

2.3.4 Simulation Process

（1）Parameter Setting: The material, color, and surface condition of materials determine the absorption, reflection, and transmission performance of light, significantly impacting building daylighting. Parameter values must be selected based on actual material properties during simulation analysis. The parameters used in this simulation analysis are shown in Table 2.2.

Table 2.2 Parameter settings table

Construction Part	Interior Finish Reflectance	Visible Light Transmittance
Walls	0.85	--
Ceilings	0.85	--
Floors	0.85	--
External Glass Curtain Wall	--	0.91

（2）Grid Division: The grid divisions for the pre-renovation and post-renovation models are shown in Figure 2.9 and Figure 2.10, respectively.

（3）Simulation Conditions:

① Daylight Factor and Illuminance Calculation: Time-by-time dynamic calculation

② CIE Sky Model (Glare Calculation): Overcast sky

③ Dynamic Calculation Interval: January 1st to December 31st

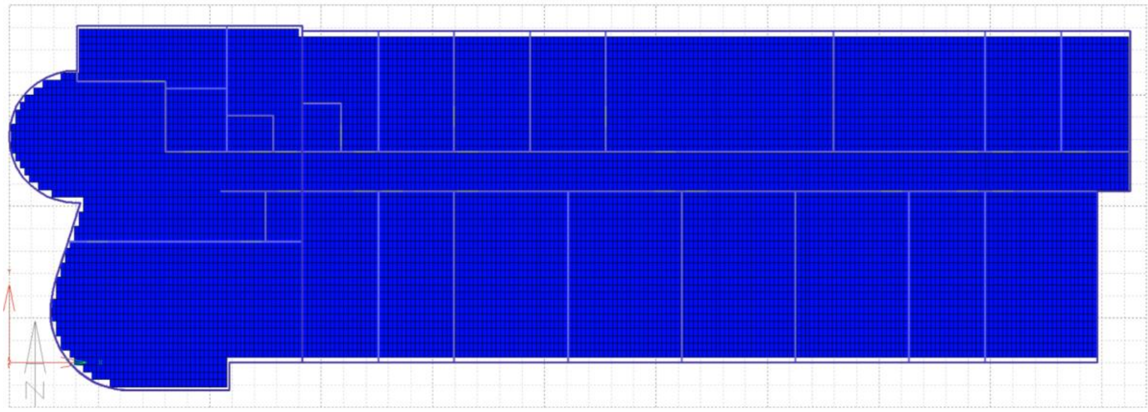

Figure 2.9 Grid division of the pre-renovation model

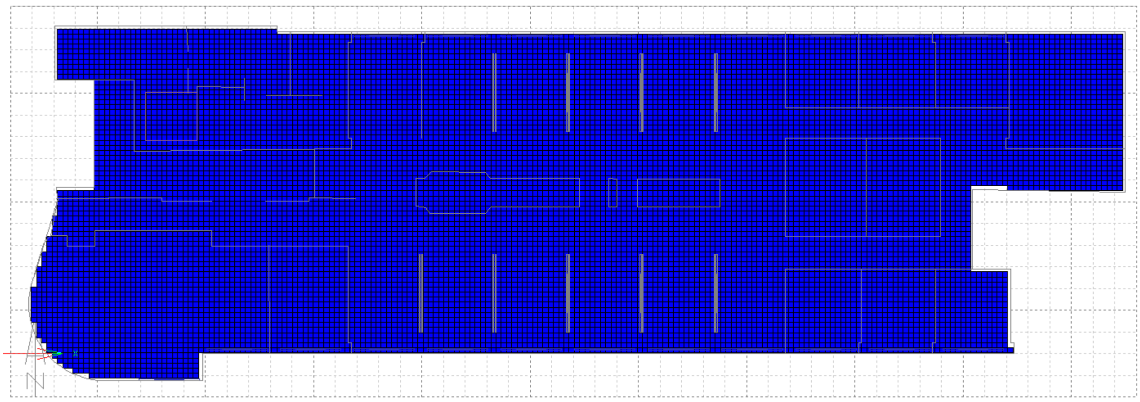

Figure 2.10 Grid division of the post-renovation model

2.3.5 Simulation Results

（1）Specified Date Simulation: An all-day illuminance simulation was conducted for an overcast day in early October, from 8:00 to 18:00.

The results show that under overcast autumn sky conditions, in the renovated building, except for the small meeting room, its surrounding corridor, and the main entrance corridor, the proportion of time with illuminance above 450 lx exceeds 50%. The main office space and large meeting room exceed 60-80%. This indicates that the lighting energy consumption in the main functional spaces is very low during autumn days; even under the most unfavorable conditions, they only need to operate at 50% lighting power.

For the pre-renovation building, the proportion of time with illuminance above 450 lx in the central corridor area was less than 10%, requiring year-round artificial lighting. North-facing rooms had a proportion below 60%, while south-facing rooms had a proportion between 60% and 80% or higher.

（2）Annual Daylighting Compliance Simulation: Using 450 lx as the standard, a simulation analysis of the annual proportion of time with compliant daylighting was conducted.

The area distribution of the post-renovation office building's compliant illuminance time proportion is shown in Table 2.3: When the compliant time proportion is in the 0% – 10% range, artificial lighting at 50% power is needed all day, corresponding to an area of 14.35%; when the compliant time proportion is in the 90% – 100% range, it can fully rely on natural daylighting, with an area proportion of 41.64%; areas with a compliant time proportion of 10% – 90% need artificial lighting for half the day, with an area proportion of 44.01%. This shows that after renovation, the area proportion in the 90% – 100% compliant time range is relatively high, while the proportion in the 0% – 10% range is relatively low.

Table 2.3 Post-renovation annual illuminance time-area ratio (450 lx standard)

Time Proportion %	Number of Points	Area Percentage %	Cumulative Points	Cumulative Area Percentage %
0-10	1317	14.35	8871	100.00
10-20	99	1.08	7861	88.61
20-30	173	1.88	7762	87.50

30-40	151	1.65	7589	85.55
40-50	241	2.63	7438	83.85
50-60	195	2.12	7197	81.13
60-70	386	4.21	7002	78.93
70-80	911	9.93	6616	74.58
80-90	2011	21.91	5705	64.31
90-100	3694	40.25	3694	41.64

The area distribution of the pre-renovation office building's compliant illuminance time proportion is shown in Table 2.4: When the compliant time proportion is in the 0%–10% range, artificial lighting at 50% power is needed all day, corresponding to an area of 21.17%; when the compliant time proportion is in the 90%–100% range, it can fully rely on natural daylighting, with an area proportion of 32.35%; areas with a compliant time proportion of 10%–90% need artificial lighting for half the day, with an area proportion of 46.48%.

Table 2.4 Pre-renovation annual illuminance time-area ratio (450 lx standard)

Time Proportion %	Number of Points	Area Percentage %	Cumulative Points	Cumulative Area Percentage %
0-10	1878	21.17	8871	100.00
10-20	301	3.39	6993	78.80
20-30	408	4.60	6692	75.41
30-40	253	2.85	6284	70.81
40-50	299	3.37	6031	67.96
50-60	160	1.80	5732	64.59
60-70	297	3.34	5572	62.79
70-80	706	7.95	5275	59.45
80-90	1699	19.15	4569	51.5
90-100	2870	32.35	2870	32.35

2.3.6 Lighting Energy Estimation and Comparison

Based on the simulation results, the annual lighting energy consumption was estimated and compared with the actual pre-renovation electricity usage. The calculation for the total annual energy cost is shown in Formula (2.1). The results, presented in Table 2.5, show that the annual lighting energy cost after renovation was reduced by 18,500 yuan, down to 15% of the pre-renovation cost.

$$F=P\times A\times H_d\times D_w\times C_e \quad (2.1)$$

In Formula (2.1), F is the total annual lighting energy cost (yuan); P is the unit area lighting power (W/m²), calculated as 12 W/m² pre-renovation and 5 W/m² post-renovation; A is the usage area (m²), calculated as 680 m²; Hd is the daily lighting duration (h/d), calculated as 10 h/d; Dw is the number of working days per year (days), calculated as 250 days; Ce is the electricity tariff (yuan/kWh), calculated as 1.0726 yuan/kWh.

Table 2.5 Comparison of annual lighting energy consumption

	Compliant Illuminance Time Ratio	Area Proportion	Unit Lighting Power （kW/m²）	Usage Area （m²）	Daily Lighting Time （h/d）	Working Days （days）	Electricity Tariff (yuan/kWh)	Annual Lighting Cost (yuan)
Post-renovation	0-10zone	14.35%	5	97.58	10	250	1.0726	1308.30
	10-90zone	44.01%	5	299.27	5	250	1.0726	2006.22
	90-100zone	41.64%	5	283.15	0	250	1.0726	0.00
Post-renovation Total			1.82	680.00	10	250	1.0726	3314.52
Pre-renovation			12	680.00	10	250	1.0726	21881.04

3 Wind Environment Analysis

3.1 Wind Environment Design

3.1.1 Open-Plan Area

In the renovated building’s open-plan area, exterior windows are reasonably arranged on both the north and south sides. These windows are operable and ensure sufficient opening area. Combined with the core requirements of natural ventilation design for office buildings, this effectively creates a complete north-south ventilation corridor, ensuring a good north-south through-flow effect in the open-plan space. The core driving force of natural ventilation comes from the synergistic effect of wind pressure difference and thermal buoyancy. The symmetrically arranged exterior windows on the north and south sides can fully utilize the wind pressure difference caused by the dominant outdoor wind direction: the windward south-facing windows form a positive pressure zone, while the leeward north-facing windows form a negative pressure zone, driving air smoothly from south to north and achieving effective indoor-outdoor air exchange. Simultaneously, this double-sided window layout aligns with the basic principles of natural ventilation optimization for office buildings. It can remove indoor waste heat and pollutants through the north-south airflow, improve indoor air quality, enhance office comfort, and reduce the usage frequency of mechanical ventilation systems, achieving building energy-saving goals. This highly aligns with the conclusion from relevant ventilation engineering studies that "reasonable window layout is key to enhancing the efficiency of natural ventilation in buildings"[15]. Furthermore, computational fluid dynamics research indicates that symmetrically placed exterior windows in large building spaces effectively reduce airflow resistance and improve ventilation uniformity. The "cross-ventilation" formed by ventilation openings on both sides of a building can promote the dilution of particulate pollutants along the block, with greater dilution effects at larger opening degrees. Compared to single-side window openings, its ventilation efficiency can be significantly improved, further confirming the rationality and scientific validity of this renovation design regarding ventilation performance[16].

3.1.2 Large Meeting Room Area

The renovated large meeting room features operable exterior windows on both its south and west walls. The window selection considers the meeting room's spatial dimensions and ventilation needs, using appropriate window types and opening methods to ensure sufficient ventilation area, resulting in good natural ventilation conditions indoors. The realization of natural ventilation depends on the interaction of outdoor wind direction, air pressure, and indoor thermal environment. The layout of operable windows in two directions (south and west) can fully utilize the dominant wind directions at different times. When outdoor wind comes from the south or west, airflow can directly enter the room through the opened windows on the corresponding side, forming reasonable indoor air circulation and effectively expelling accumulated carbon dioxide, waste heat, and other air pollutants. This multi-directional window layout overcomes the ventilation limitations of single-direction openings. Even during variable wind direction periods, smooth indoor air circulation can be maintained by adjusting the opening angles of windows on different sides, ensuring good indoor air quality and thermal comfort, meeting the practical natural ventilation needs of office meeting rooms. This design concept aligns with relevant ventilation engineering research conclusions, which point out that arranging operable exterior windows on multiple sides of a room effectively improves the stability and effectiveness of natural ventilation, avoiding dead ventilation zones caused by single-side opening designs, especially suitable for meeting rooms with high occupancy requiring adequate air exchange[16-17].

3.1.3 Small Office Area

The renovated small offices, due to their small spatial scale, low internal personnel density, and limited waste heat and pollutant emissions from daily work, only require operable exterior windows on a single side to meet core daily ventilation needs. The ventilation requirements of small offices differ significantly from open-plan spaces and meeting rooms, not requiring complex ventilation corridors. The single-side operable window, driven by indoor-outdoor wind pressure and thermal buoyancy differences, can achieve effective air circulation: outdoor fresh air enters through the opened window, gradually displacing indoor stale air, expelling accumulated carbon dioxide, office equipment heat, and small amounts of pollutants, thus maintaining indoor air quality within acceptable limits and ensuring occupant comfort and work efficiency. This single-side window design simplifies the renovation construction process, reduces costs, and meets the practical ventilation needs of small offices, balancing practicality and economy, consistent with existing research findings on small space ventilation in office buildings.

3.2 Wind Environment Analysis Tools

Vento AEC is a Computational Fluid Dynamics (CFD) software developed by the Italian company VENTO CFD, specifically designed for the architecture, engineering, and construction (AEC) industry. The software uses non-conformal mesh technology as its core, significantly shortening the preprocessing time for complex geometric models and achieving seamless integration with IFC standard models, eliminating the dependence on geometric simplification common in traditional CFD tools. In terms of application, Vento AEC supports wind load calculations, indoor/outdoor thermal comfort assessments, and pollutant dispersion simulations, with its calculation results showing good consistency with wind tunnel tests and industry benchmark software in multiple benchmark tests. By significantly lowering the technical operation threshold, the software enables architects and engineers without specialized fluid mechanics backgrounds to directly conduct wind environment simulations in the early design stages, providing an efficient technical pathway for building performance optimization and enhancing productivity for the design team.

3.3 Pre-renovation Wind Environment Simulation of the Office Building

3.3.1 Model Import and Processing

（1）Import the pre-renovation model into Vento. At this stage, all parts of the model form a single entity, and the system defaults its name to "unknown". Processing is required to facilitate analysis.

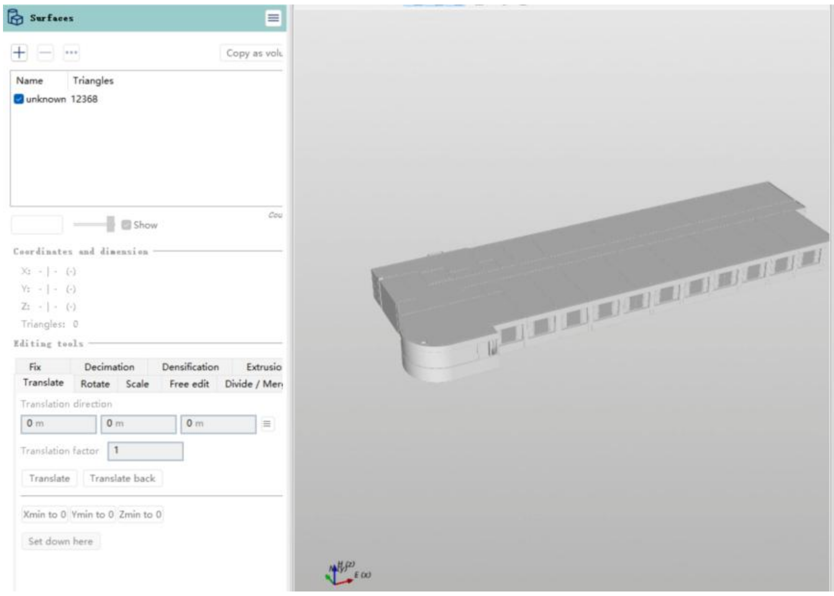

Figure 3.1 Unprocessed model after import into Vento

(2) Separate the upper surface of the model (i.e., the ceiling of the office building) from the whole, individually refine it, and name it "ceiling". Deselect the "ceiling" part, as shown in Figure 3.2. Since the model has thickness, this operation must be repeated to see the model beneath the ceiling.

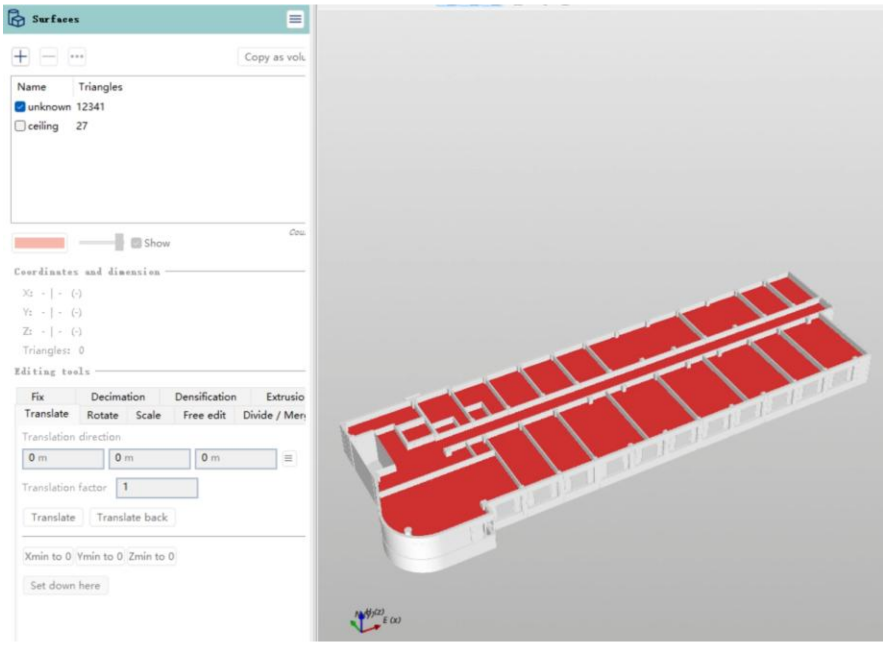

Figure 3.2 Model after individually refining the ceiling

(3) After repeating the above operation, merge the two separated ceiling parts to get the new "ceiling" part. Increasing the transparency of the "ceiling" part to maximum or

deselecting it reveals the internal structure of the pre-renovation office building.

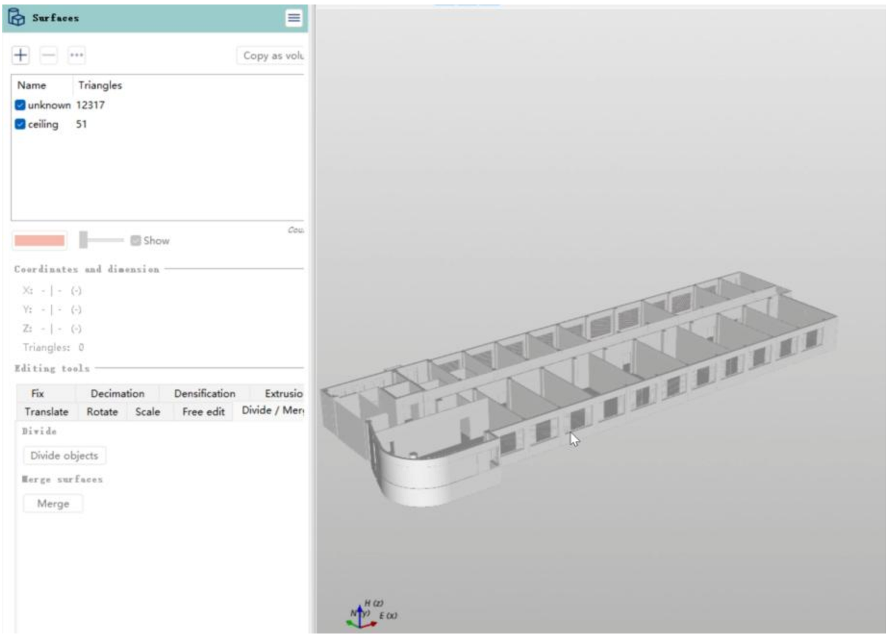

Figure 3.3 Internal structure of the pre-renovation office building

(4) For wind environment simulation, the most critical aspect is simulating the permeable parts (i.e., the window sections). The windows of this office building are fitted with louvers. Due to the small gaps between the louver slats, it is necessary to individually select the louver sections and set a smaller mesh size to meet simulation requirements. The louver selection process is shown in Figure 3.4; this operation must be repeated for each set of louvers in the building.

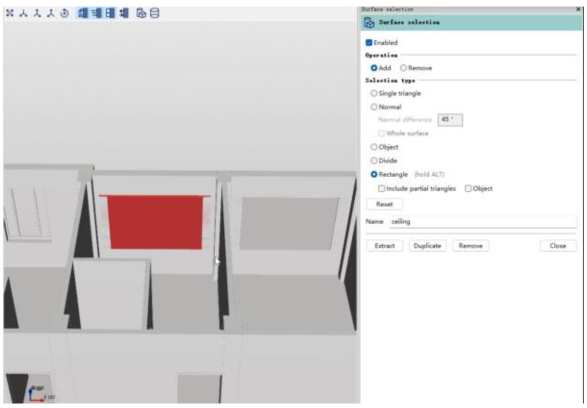

Figure 3.4 Schematic diagram of the louver selection process

(5) After selecting all louvers, the preprocessed model is obtained, as shown in

Figure 3.5.

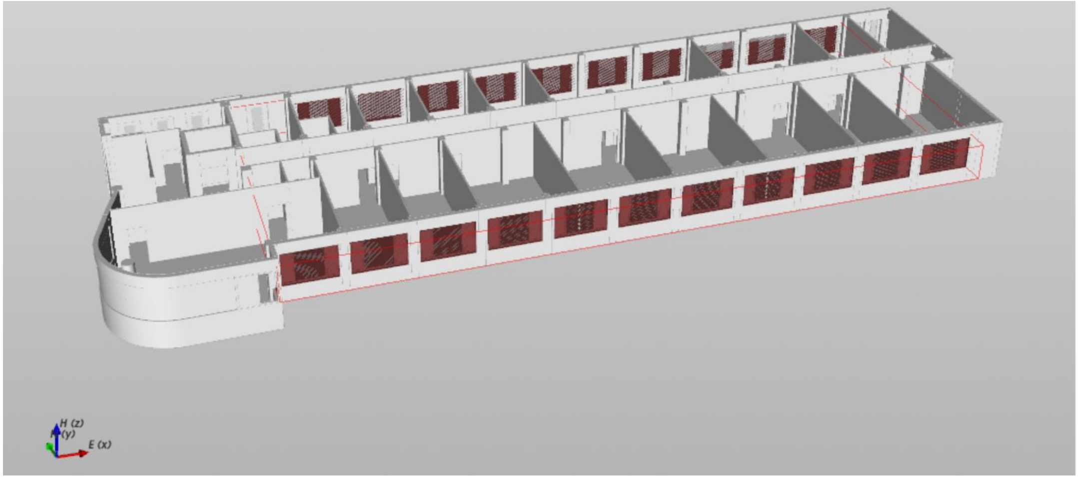

Figure 3.5 Preprocessed model

3.3.2 Mesh Settings

Smaller mesh sizes yield more accurate simulation results. However, excessively small mesh sizes lead to an overwhelming number of mesh elements, making it impossible for the computer to run the software normally. Therefore, to operate normally and achieve as accurate results as possible, after repeated testing, the normal and tangential parameters for the "ceiling" part were set to 1, the normal parameter for the "room" part was set to 0.3, and both the normal and tangential parameters for the "louver" part were set to 0.04. Ultimately, the number of mesh cells for the "ceiling" part was 51, for the "room" part was 7602, and for the "louver" part was 4715. The meshing condition is shown in Figure 3.6.

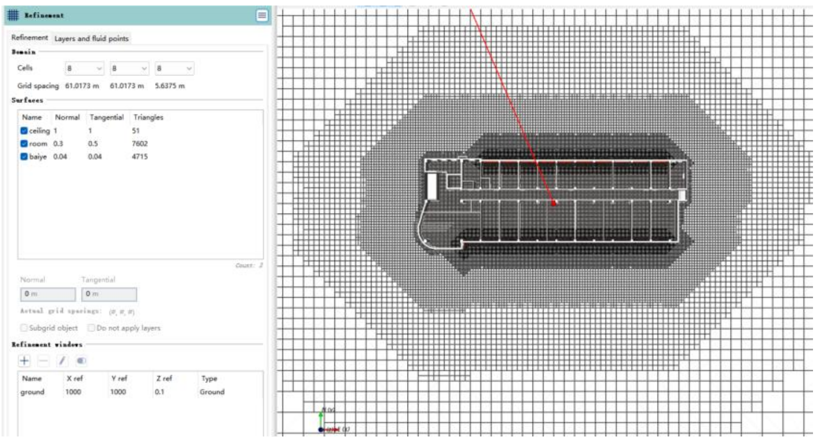

Figure 3.6 Meshing condition

3.3.3 Meteorological Parameters

Typical meteorological year data for Shanghai is shown in Figure 3.7, presenting only wind direction frequency and average wind speed for different seasons. The overall natural ventilation simulation was conducted using the highest frequency condition for autumn: wind direction NNE, wind speed 3.8 m/s, temperature set to 30 ℃, and pressure set to 101325 Pa. For thermal comfort analysis, 16 autumn conditions were used for calculation.

风向	春季		夏季		秋季		冬季	
	风向频率%	平均风速 m/s	风向频率%	平均风速 m/s	风向频率%	平均风速 m/s	风向频率%	平均风速 m/s
N	3.88	4.5	1.94	2.7	10.96	3.4	11.05	3.8
NNE	9.7	4.3	4.43	3.3	**14.41**	**3.8**	14.24	3.5
NE	5.54	4.0	9.97	3.8	8.93	3.5	10.76	3.2
ENE	8.86	3.6	13.57	3.5	10.09	3.9	7.56	2.7
E	7.76	3.7	11.91	3.4	7.78	3.4	4.94	2.1
ESE	**11.91**	**3.8**	**14.96**	**3.4**	5.48	3.1	6.40	2.6
SE	6.93	2.8	8.59	2.5	6.63	2.0	2.91	1.9
SSE	8.59	2.0	6.09	3.0	2.59	3.1	1.45	2.4
S	5.26	2.7	6.65	3.8	2.31	2.4	2.62	3.9
SSW	6.09	2.9	6.65	3.8	2.31	3.0	1.16	5.5
SW	6.09	3.3	6.65	3.9	1.44	2.4	2.62	2.9
WSW	2.22	2.3	2.49	3.0	2.59	2.1	4.36	2.3
W	2.77	3.2	3.60	2.5	5.48	2.3	6.69	2.7
WNW	6.65	3.5	0.55	3.0	3.75	3.1	5.52	3.6
NW	3.88	3.9	0.55	2.5	2.31	3.4	5.81	4.4
NNW	3.88	4.7	1.39	2.8	12.97	4.4	**11.92**	**3.9**

Figure 3.7 Typical meteorological year data for Shanghai

3.3.4 Pre-renovation Overall Natural Ventilation Simulation Results

Based on the data in Figure 3.7, the highest wind direction frequency condition for Shanghai's autumn was selected to simulate the pre-renovation overall natural ventilation: wind direction NNE, average wind speed 3.8 m/s, air temperature set to the maximum autumn temperature in Shanghai of 30 ℃, pressure at one standard atmosphere 101325 Pa. The wind speed cross-section was taken at a height of 2 meters from the floor. The wind speed contour map is shown in Figure 3.8. It can be seen that the natural ventilation effect in the pre-renovation rooms was poor. Except for areas directly opposite the windows, where wind speeds were slightly higher, the natural ventilation wind speed in most other parts was basically below 0.3 m/s. This indicates that the pre-renovation spatial natural ventilation condition was poor, and the wind speed difference between areas directly opposite windows and other areas was large, resulting in poor wind speed field uniformity.

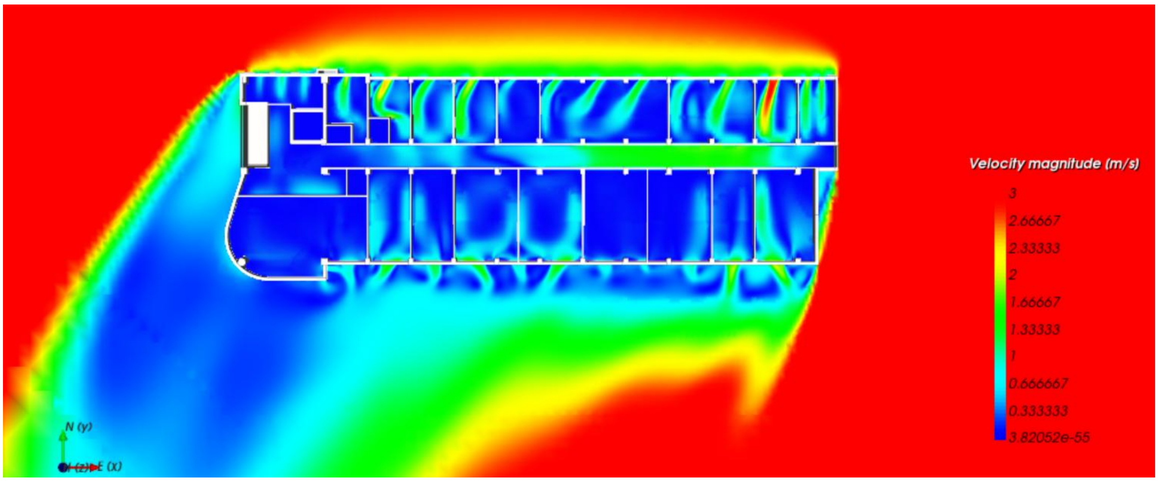

Figure 3.8 Pre-renovation overall natural ventilation

3.3.5 Overall Natural Ventilation with Internal Heat Sources Added

To make the simulation results more convincing, an additional set of conditions was simulated: overall natural ventilation with added internal heat sources. The specific steps are as follows:

（1）As shown in Figure 3.9, first add cylindrical surfaces at suitable locations within the room.

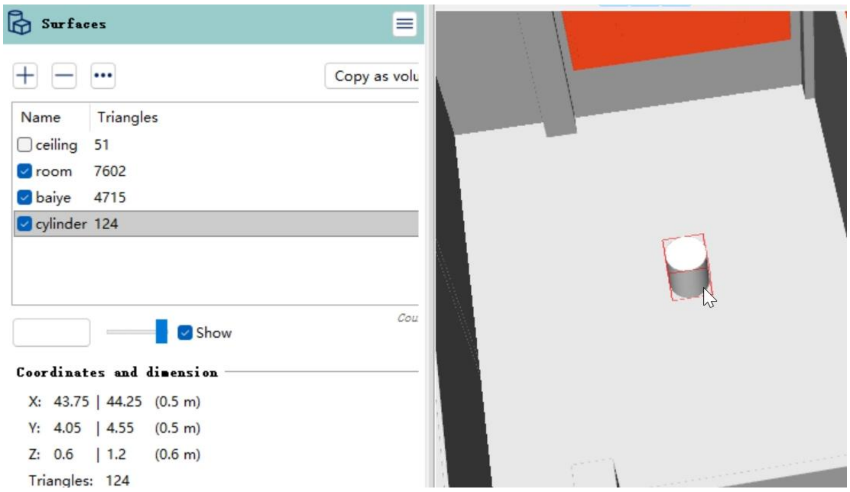

Figure 3.9 Adding cylindrical surfaces at suitable locations in the room

（2）Since this experimental scheme only analyzes the effect of heat source heat generation on wind speed and does not consider the obstruction of natural wind by objects inside the room, the above cylindrical surfaces were copied as volumetric internal heat sources with a heat flux density set to 60 W, and the original cylindrical surfaces were deleted. This operation was repeated several times to obtain the schematic of the condition with added internal heat sources, shown in Figure 3.10.

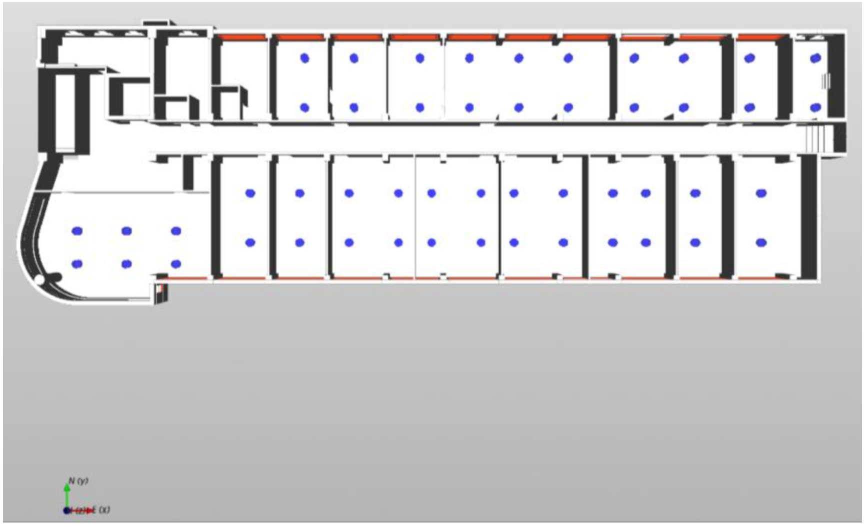

Figure 3.10 Schematic diagram of the condition with added internal heat sources

（3）Except for the added internal heat sources, all other parameters remained consistent with the condition without internal heat sources. The simulation result is shown in Figure 3.11. The results indicate that the natural ventilation wind speed in most areas of the pre-renovation office building was basically below 0.3 m/s, and the wind speed uniformity was poor. This further demonstrates that the pre-renovation building's natural ventilation effect was poor.

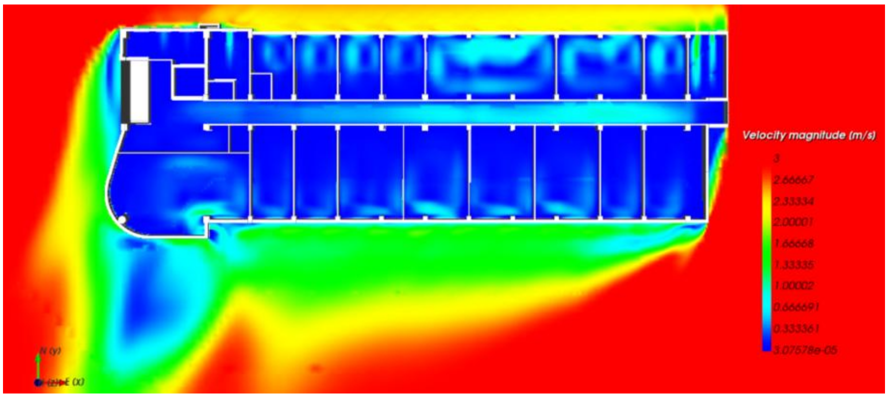

Figure 3.11 Wind speed contour map with added internal heat sources

3.4 Pre-renovation Thermal Comfort Calculation and Analysis

3.4.1 Thermal Comfort Calculation Process

（1）Calculation Zone Selection: To analyze the pre-renovation thermal comfort of the office building, five zones were selected as shown in Figure 3.12, named volume1, volume2, volume3, volume4, and volume5. The slice thickness was 1.5 m.

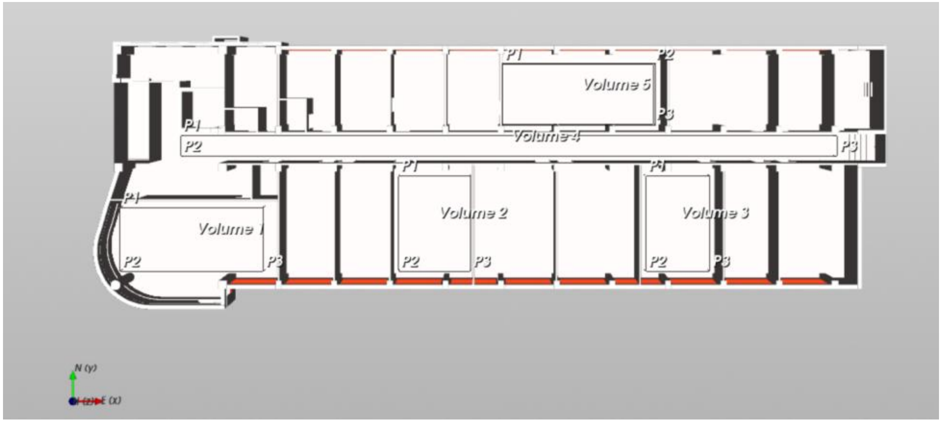

Figure 3.12 Thermal comfort calculation zones

（2）Parameter Settings: Sixteen autumn conditions were set according to wind directions, with the wind direction frequencies and average wind speeds shown in Table 3.1. Other parameter settings are as follows:

① Air Dry-bulb Temperature: Two groups were set, with temperatures of 30 ℃ and 28 ℃ respectively.

② Mean Radiant Temperature: Based on experience, when the outdoor temperature is 30 ℃ or 28 ℃, the indoor mean radiant temperature is around 27 ℃. Therefore, two groups of mean radiant temperatures were set: 27 ℃ and 27.5 ℃.

③ Relative Humidity: In the Vento software, the general baseline value for autumn conditions in Shanghai was used, set at 70%.

④ Metabolic Rate: Assuming office staff performing light office work, the metabolic rate was set to 1 met.

⑤ Clothing Insulation: Set to 0.57 clo.

3.4.2 Calculation Results

When the outdoor air dry-bulb temperature was 30 ℃, the thermal comfort calculation results are shown in Table 3.1. The results show that at 30 ℃, the PMV values in all zones of the office building were basically outside the ±1 range, indicating poor thermal comfort and the need to turn on air conditioning.

When the outdoor air dry-bulb temperature was 28 ℃, the thermal comfort calculation results are shown in Table 3.2. The results show that at 28 ℃, the PMV values in all zones of the office building were basically outside the ±0.5 range, with only a few cases meeting the strict ±0.5 thermal comfort interval. Thermal comfort was poor, requiring air conditioning.

Table 3.1 Thermal Comfort Calculation Table 1

Wind	Dir.Freq %	Avg.Speed m/s	Temp ℃	RH %	Rad.Temp ℃	Met.rate met	met clo	zone1	zone2	zone3	zone4	zone5
N	10.96	3.4			27			1.01	0.96	0.98	0.89	1.21
					27.5			1.07	1.02	1.04	0.95	1.30
NNE	14.41	3.8			27			1.02	0.88	0.95	0.85	1.07
					27.5			1.08	0.94	1.01	0.90	1.14
NE	8.93	3.5			27			1.01	0.89	0.87	0.83	0.94
					27.5			1.08	0.95	0.93	0.88	1.00
ENE	10.09	3.9			27			1.01	0.87	0.87	0.82	0.89
					27.5			1.07	0.93	0.92	0.87	0.94
E	7.78	3.4			27			1.01	0.89	0.90	0.84	0.90
					27.5			1.07	0.95	0.96	0.89	0.96
ESE	5.48	3.1			27			1.04	0.95	0.96	0.91	1.24
					27.5			1.11	1.01	1.02	0.97	1.32
SE	6.63	2	30	70	27	1	0.57	1.09	1.07	1.04	0.96	1.23
					27.5			1.16	1.14	1.11	1.02	1.31
SSE	2.59	3.1			27			1.00	0.96	0.95	0.89	1.19
					27.5			1.07	1.02	1.01	0.95	1.27
S	2.31	2.4			27			1.09	1.04	1.03	0.95	1.21
					27.5			1.17	1.11	1.10	1.01	1.29
SSW	2.31	3			27			1.10	0.95	0.95	0.92	1.20
					27.5			1.17	1.02	1.01	0.98	1.28
SW	1.44	2.4			27			1.28	1.21	1.26	1.19	1.25
					27.5			1.37	1.29	1.34	1.27	1.33
WSW	2.59	2.1			27			1.33	1.25	1.31	1.21	1.33
					27.5			1.42	1.34	1.40	1.30	1.42
W	5.48	2.3			27			1.31	1.30	1.33	1.14	1.33

					27.5			1.40	1.39	1.42	1.22	1.42
WNW	3.75	3.1			27			1.20	1.25	1.29	1.19	1.26
					27.5			1.28	1.34	1.38	1.27	1.34
NW	2.31	3.4			27			1.09	1.17	1.21	1.17	1.21
					27.5			1.16	1.25	1.29	1.24	1.29
NNW	12.97	4.4			27			1.03	1.10	1.13	1.10	1.14
					27.5			1.10	1.17	1.21	1.17	1.22

Table 3.2 Thermal Comfort Calculation Table 2

Wind	Dir.Freq %	Avg. Speed m/s	Temp ℃	RH %	Rad.Temp ℃	Met.rate met	met clo	zone 1	zone2	zone 3	zone 4	zone 5
N	10.96	3.4			27			0.51	0.86	0.90	0.64	0.94
					27.5			0.59	0.95	0.99	0.72	1.02
NNE	14.41	3.8			27			0.51	0.55	0.57	0.55	0.60
					27.5			0.58	0.62	0.64	0.62	0.67
NE	8.93	3.5			27			0.71	0.86	0.72	0.54	0.80
					27.5			0.79	0.95	0.80	0.61	0.89
ENE	10.09	3.9			27			0.47	0.49	0.47	0.37	0.34
					27.5			0.54	0.56	0.54	0.44	0.40
E	7.78	3.4			27			0.49	0.48	0.48	0.32	0.36
					27.5			0.56	0.55	0.55	0.39	0.43
ESE	5.48	3.1			27			0.79	0.83	0.70	0.50	0.75
					27.5			0.87	0.91	0.78	0.58	0.83
SE	6.63	2	28	70	27	1	0.57	0.78	0.88	0.75	0.67	0.81
					27.5			0.86	0.97	0.83	0.75	0.90
SSE	2.59	3.1			27			0.64	0.76	0.74	0.61	0.73
					27.5			0.71	0.85	0.83	0.68	0.82
S	2.31	2.4			27			0.80	0.83	0.82	0.70	0.77
					27.5			0.88	0.92	0.91	0.78	0.85
SSW	2.31	3			27			0.78	0.75	0.77	0.65	0.72
					27.5			0.87	0.83	0.85	0.73	0.80
SW	1.44	2.4			27			0.87	0.73	0.87	0.66	0.83
					27.5			0.95	0.81	0.95	0.74	0.91
WSW	2.59	2.1			27			0.94	0.82	0.94	0.74	0.94
					27.5			1.02	0.91	1.02	0.82	1.02
W	5.48	2.3			27			0.63	0.94	0.94	0.94	0.94

			27.5	0.70	1.02	1.02	1.02	1.02
WNW	3.75	3.1	27	0.62	0.50	0.56	0.34	0.42
			27.5	0.69	0.58	0.63	0.41	0.49
NW	2.31	3.4	27	0.47	0.79	0.84	0.40	0.81
			27.5	0.54	0.88	0.92	0.47	0.90
NNW	12.97	4.4	27	0.39	0.39	0.57	0.53	0.59
			27.5	0.46	0.58	0.65	0.67	0.66

Comparing the conditions with outdoor air dry-bulb temperatures of 28 ℃ and 30 ℃, the following conclusions can be drawn:

① Significant impact of temperature on thermal comfort: When the air dry-bulb temperature dropped from 30 ℃ to 28 ℃, the PMV values across all wind directions and zones decreased significantly overall. Most zones returned from a hot-biased state to near the comfort zone, indicating that indoor air temperature is a key factor determining thermal comfort levels, and cooling can markedly improve human thermal sensation.

② Increase in mean radiant temperature increases PMV: Under the same temperature, humidity, and wind speed, increasing the mean radiant temperature from 27 ℃ to 27.5 ℃ raised PMV in all zones, making the human body feel warmer. This shows that the radiant cooling effect brought by enclosure structures and shading has a stable and quantifiable impact on comfort.

③ Increased natural ventilation wind speed improves thermal comfort: From the data across different wind directions, higher outdoor average wind speeds generally correspond to lower indoor PMV. For example, wind directions with higher wind speeds like NNW, NNE, and ENE showed significantly better indoor thermal comfort than those with lower wind speeds like SW, WSW, and W. Airflow from natural ventilation effectively alleviates stuffiness.

④ Distinct comfort differences across zones, with local overheating: Under the same conditions, PMV values were not consistent across the five zones. Some zones (e.g., Zone 5, Zone 1) were more prone to higher PMV under low wind speed directions, indicating that ventilation effectiveness varies at different locations within the room; areas closer to the ventilation path are more comfortable, while locations distant from openings or obstructed areas are warmer.

⑤ Thermal comfort differences caused by different air dry-bulb temperatures: Under the 30 ℃ condition, PMV values for almost all wind directions and zones were >0.8, with some exceeding 1.3, indicating overall overheating. At 28 ℃, PMV in most zones dropped to between 0.4–1.0, and many zones entered the ±0.5 thermal comfort range.

⑥ Importance of dominant wind directions: NNW, N, and NNE have high wind direction frequencies, higher wind speeds, and lower PMV values. These are the dominant wind directions for improving indoor thermal comfort in autumn. Building window openings and layouts should prioritize utilizing these wind directions to enhance ventilation efficiency.

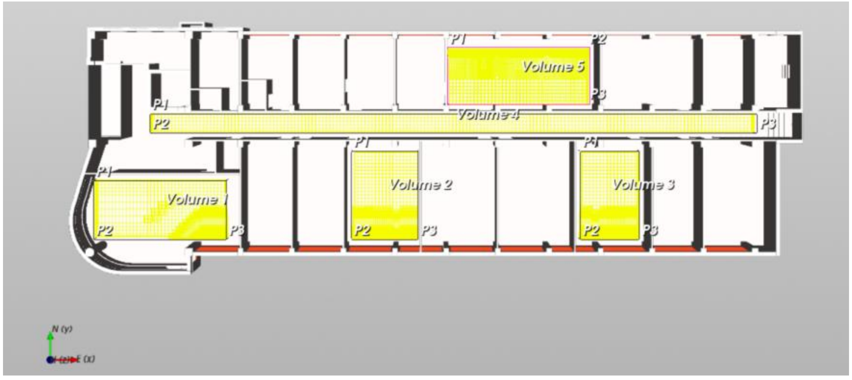

Figure 3.13 Thermal comfort calculation result contour map

3.5 Post-renovation Wind Environment Simulation Results and Thermal Comfort Status

3.5.1 Post-renovation Overall Natural Ventilation Simulation Results

Simulation was conducted using the highest frequency autumn condition (wind direction NNE, wind speed 3.8 m/s). The wind speed cross-section was taken at a height of 2 meters from the floor. The wind speed contour map is shown in Figure 3.14. It can be seen that the renovated open-plan office area has a strong natural ventilation effect, with wind speeds between 0.3 m/s and 0.6 m/s. The average wind speed is higher than that of the pre-renovation condition, and the wind speed uniformity is also better than the pre-renovation condition.

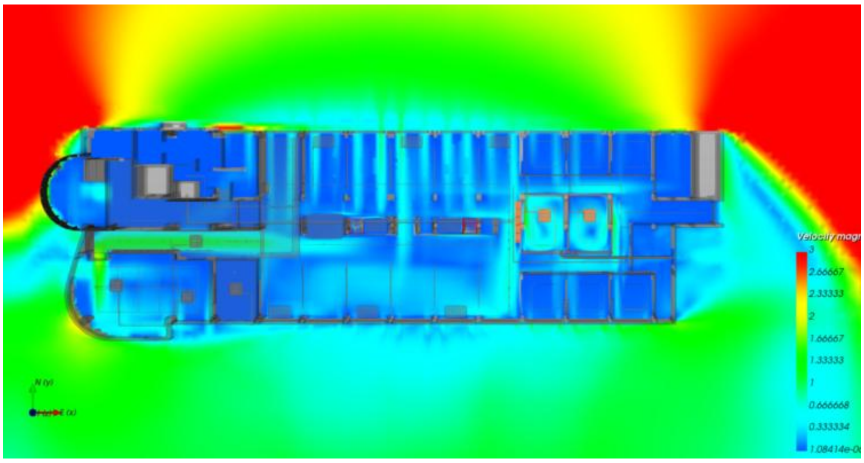

Figure 3.14 Post-renovation overall natural ventilation wind speed contour map

3.5.2 Post-renovation Thermal Comfort Status

For the calculation conditions, sixteen autumn conditions were set according to wind direction, with the wind direction frequencies and average wind speeds shown in Table 3.1. Air dry-bulb temperature was set in two groups: 30 ℃ and 28 ℃. Based on experience, when the outdoor temperature is 30 ℃ or 28 ℃, the indoor mean radiant temperature is around 27 ℃. Therefore, two groups of mean radiant temperatures were set: 27 ℃ and 27.5 ℃. In Vento software, the general baseline value for relative humidity under Shanghai autumn conditions was used, set at 70%. Metabolic rate was set to 1 met, assuming light office work. Clothing insulation was set to 0.57 clo.

It was assumed that air conditioning is fully on for the six months of winter and summer. Based on analysis of Shanghai's climate, spring and autumn have similar climatic conditions, so the thermal comfort and air conditioning usage scenario for spring can reference the autumn data, eliminating the need for redundant calculations.

The weather conditions for autumn (September to November) were selected for simulating and analyzing the PMV thermal comfort of the entire environment. It was set that air conditioning is turned on when the outdoor temperature exceeds 28 ℃ in spring and autumn, so only conditions with outdoor temperatures not exceeding 28 ℃ were analyzed.

As shown in Table 3.3, under an autumn air dry-bulb temperature of 28 ℃, even according to the very strict indoor thermal comfort requirement of PMV ±0.5, only very few instances fell outside the comfort range. If using the general thermal comfort requirement of PMV ±1, it can be satisfied when the outdoor temperature does not exceed 30 ℃.

According to Shanghai meteorological data, there are approximately 90 days per year where the daily minimum outdoor temperature is above 18 ℃ and the maximum temperature is below 30 ℃. After renovation, the office building does not need to use air conditioning for 90 days a year, compared to only 30 days before renovation.

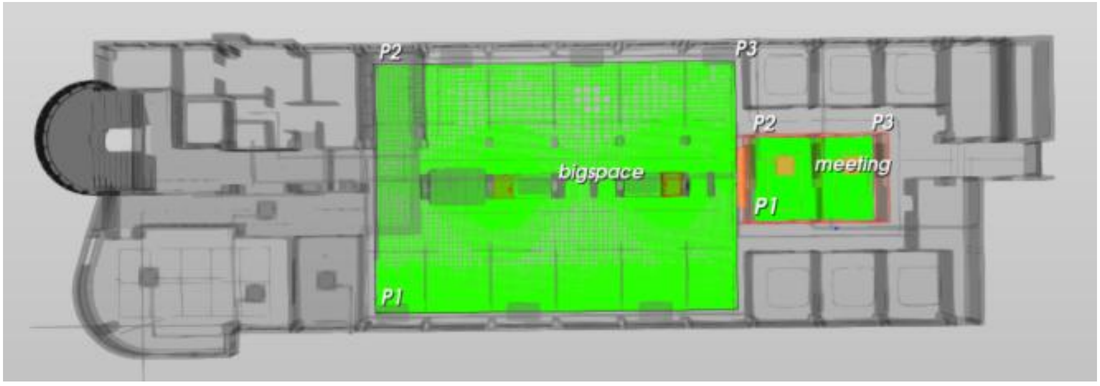

Figure 3.15 Selection of thermal comfort calculation zones for the post-renovation building

The selection of thermal comfort calculation zones for the post-renovation building is shown in Figure 3.15. Five zones were selected: Open-plan Space, Large Meeting Room, Small Meeting Room, Phone Booth 1, and Phone Booth 2. The PMV calculation results for these five zones are shown in Table 3.3.

Table 3.3 Thermal Comfort Calculation Table 3

Wind	Dir.Freq %	Avg.Speed m/s	Temp °C	RH %	Rad.Temp °C	Met.rate met	met clo	Open-plan	Small Meeting	Phone Booth1	Phone Booth2	Large Meeting
N	10.96	3.4	28	70	27	1	0.57	0.44	0.18	0.42	0.42	0.40
					27.5			0.50	0.24	0.49	0.49	0.47
NNE	14.41	3.8			27			0.41	0.30	0.32	0.32	0.45
					27.5			0.47	0.37	0.38	0.38	0.52
NE	8.93	3.5			27			0.27	0.29	0.42	0.42	0.20
					27.5			0.33	0.35	0.49	0.49	0.26
ENE	10.09	3.9			27			0.37	0.46	0.42	0.42	0.49
					27.5			0.43	0.54	0.49	0.49	0.46

E	7.78	3.4	27	0.40	0.36	0.43	0.43	0.71
			27.5	0.47	0.43	0.50	0.50	0.79
ESE	5.48	3.1	27	0.29	0.41	0.41	0.41	0.21
			27.5	0.35	0.48	0.48	0.48	0.27
SE	6.63	2	27	0.57	0.47	0.38	0.38	0.54
			27.5	0.65	0.54	0.45	0.45	0.62
SSE	2.59	3.1	27	0.63	0.40	0.37	0.37	0.50
			27.5	0.71	0.47	0.40	0.40	0.57
S	2.31	2.4	27	0.49	0.41	0.39	0.39	0.45
			27.5	0.68	0.48	0.46	0.46	0.52
SSW	2.31	3	27	0.41	0.29	0.34	0.34	0.42
			27.5	0.48	0.35	0.40	0.40	0.49
SW	1.44	2.4	27	0.40	0.40	0.36	0.36	0.5
			27.5	0.47	0.47	0.43	0.43	0.57
WSW	2.59	2.1	27	0.37	0.60	0.41	0.41	0.4
			27.5	0.44	0.67	0.47	0.47	0.47
W	5.48	2.3	27	0.31	0.62	0.45	0.45	0.37
			27.5	0.38	0.70	0.52	0.52	0.43
WNW	3.75	3.1	27	0.28	0.40	0.44	0.44	0.15
			27.5	0.35	0.47	0.51	0.51	0.21
NW	2.31	3.4	27	0.38	0.19	0.40	0.40	0.19
			27.5	0.45	0.25	0.47	0.47	0.26
NNW	12.97	4.4	27	0.41	0.36	0.39	0.39	0.29
			27.5	0.47	0.42	0.46	0.46	0.35

3.6 Energy Analysis and Calculation

Based on CFD simulation and thermal comfort calculations (using the PMV index), comparing the data in Table 3.1, Table 3.2, and Table 3.3, and combining with typical meteorological year data for Shanghai, the annual air conditioning on/off days and corresponding energy consumption were calculated. Before renovation, due to poor ventilation organization, the cooling air conditioning needed to be activated when the outdoor daily average temperature was above 26 ℃, resulting in only 30 days a year without air conditioning. After renovation, the building's thermal comfort improved significantly, increasing the number of days without mechanical cooling to 90 days per year. The energy analysis results are shown in Table 3.4. The annual operating energy consumption of the air conditioning system decreased by 16.4% post-renovation, equivalent to an electricity cost saving of 6,176 yuan.

Table 3.4 Air Conditioning Energy Consumption Comparison Table

	Avg. Power per Unit (kW)	Number of Units	Total Power (kW)	Electricity Tariff (yuan/kWh)	Days without Use per Year	Days with Use per Year	Annual AC Electricity Cost (yuan)
Open-plan Space	1.26	6	7.536	1.0726	65	185	14953.76
Small Office	0.52	7	3.64	1.0726	65	185	7222.89
Large Meeting Room	0.96	2	1.92	1.0726	67	183	3768.69
Small Meeting Room	0.60	3	1.8	1.0726	70	180	3475.22
Other Areas	0.52	2	1.04	1.0726	70	180	2007.91
Total			15.936	1.0726			31428.47
Pre-renovation			15.936	1.0726	30	220	37604.50

4 Analysis of Human Factors Quality Improvement from the Luminous Environment Perspective

4.1 Visual Ergonomics Dimension

4.1.1 Improved Illuminance Levels and Luminance Distribution

Office workers spend most of their time indoors. Illuminance is one of the key factors affecting productivity. Daylight significantly influences workers' alertness, overall satisfaction, mood, and health. Lighting quality is crucial for cognitive processing, emotional responses, and reducing visual fatigue. Insufficient light can lead to discomfort, anxiety, and fatigue. Although both sunlight and artificial light can provide adequate illuminance, sunlight brings more emotional and physiological benefits. Sunlight, as a free and abundant resource, is a core element of architectural luminous environment design[18-19].

Studies have shown that changes in light intensity cause changes in pupil diameter. The pupil diameter, as part of the human eye, and its regulatory mechanisms are significant for establishing visual state evaluation standards[20]. Scientists like Koo monitored pupil diameter changes while subjects watched two different videos under different viewing conditions; when subjective fatigue was apparent, pupil diameter changes were also significant[21]. This indicates that changes in light intensity can trigger and exacerbate visual fatigue. The pre-renovation central corridor layout caused significant illuminance variations within the building, with marked brightness differences between areas near windows and the corridor area. During frequent gaze shifts, workers' eyes had to constantly adjust to different brightness levels, leading to increased visual fatigue.

Post-renovation, the open-plan layout expands the reach of natural light. White furniture and interior finishes are highly reflective surfaces that scatter light uniformly throughout the space via diffuse reflection, unaffected by transparent glass partitions, thereby reducing brightness differences between areas. Research suggests that a comfortable office luminous environment should be based on uniform, soft ambient lighting, avoiding excessive brightness contrast that triggers adverse reactions like visual fatigue[22].

4.1.2 Glare Control and Visual Comfort Enhancement

Glare is one of the dominant factors affecting visual comfort in office luminous environments. While the open-plan layout fully utilizes natural light, it also increases the risk of glare from direct sunlight[18]. The renovated building uses venetian blinds to regulate sunlight. Venetian blinds offer effective shading while maintaining indoor ventilation[23]. By adjusting the slat angle, direct sunlight is intercepted or refracted into diffuse light, illuminating the ceiling rather than directly entering the eyes, thus increasing natural daylight illuminance while reducing the probability of glare. Meanwhile, the blinds do not completely block the outside view, allowing workers to maintain an outward view while avoiding glare interference, which positively impacts the visual comfort of those working long hours. Research indicates that a well-designed shading system can effectively improve building facade aesthetics and reduce building energy consumption[24]. Furthermore, the zone-controlled function of the LED lighting system dynamically adjusts artificial lighting levels based on natural light changes, preventing glare superposition caused by artificial lighting itself.

4.1.3 Visual Fatigue Alleviation

Luminous environment factors such as illuminance and glare significantly affect visual comfort and fatigue levels[18-19]. The improved illuminance uniformity and controlled glare in the post-renovation luminous environment mean that workers' visual systems no longer need to continuously make large-scale light-dark adaptation adjustments. This reduces ocular muscle tension, potentially alleviating the accumulated visual fatigue from prolonged office work[25].

4.2 Physiological Health Dimension

4.2.1 Regulation of Circadian Rhythms by Natural Light

The human retina contains intrinsically photosensitive retinal ganglion cells (ipRGCs), which are particularly sensitive to blue light with a wavelength of around 485 nm. When the human eye perceives natural light in this wavelength band, light signals are transmitted via the non-visual pathway to the suprachiasmatic nucleus, regulating melatonin secretion and the cyclic operation of the circadian rhythm. Exposure to natural light in office spaces is a key environmental factor for maintaining the normal functioning of this physiological mechanism[9]. Before renovation, the office area relied heavily on artificial lighting, limiting workers' exposure to natural light. This could disrupt their circadian rhythm synchronization, manifesting as sub-health symptoms like decreased daytime alertness and reduced nighttime sleep quality[26]. The post-renovation open-plan layout increases the opportunity for and degree of indoor workers' contact with natural light, which is fundamentally significant for protecting their circadian rhythm health. Considering the impact of natural light on the human biological clock, maximizing the use of daylight in building design and renovation is an important pathway to improving human health.

4.2.2 Light Spectrum Quality and Visual Health

The white, highly reflective walls and ceilings largely preserve the spectral distribution characteristics of natural light during diffuse reflection. This means the reflected light reaching the deeper interior still has good color rendering properties, which is beneficial for maintaining normal color discrimination ability[17]. Simultaneously, the white spatial interface reduces visual stimulation caused by excessively strong color contrast, creating a visually friendly, non-overstimulating environment conducive to the long-term protection of visual function.

4.3 Psychological Perception Dimension

4.3.1 Open Space and Psychological Restoration

The pre-renovation low suspended ceiling and screen partitions created a closed, oppressive spatial feeling. Office workers in such environments for long periods were prone to mental fatigue. Post-renovation, the ceiling-free design greatly expands the vertical visual range, while the open-plan layout allows the horizontal sightline to traverse multiple functional zones. Together, these impart a sense of "spaciousness," reducing the experience of enclosure and oppression on a visual-psychological level. Although this spatial characteristic is not equivalent to a natural environment, its visual extensibility can similarly provide the conditions needed for attention restoration.

4.3.2 Environmental Control and Autonomy

The "control" theory in environmental psychology posits that when individuals perceive the ability to influence certain attributes of their environment, their psychological stress decreases, and satisfaction and comfort increase[27]. The post-renovation zone-controlled lighting system gives users unprecedented control over their luminous environment: the two linear LED lights above each row of workstations in the office area can be independently switched, allowing users to choose the number of lights to turn on based on the natural lighting conditions at their location; the grid lights in the meeting room are divided into three independent control zones, enabling flexible selection of lighting scope based on the meeting scenario. This "on-demand lighting" approach delegates the control of the light environment from the building manager to the individual user, giving users more control over their work environment. Research indicates that human-centric lighting strategies should emphasize personalized adjustment needs, enhancing user satisfaction with and sense of belonging to their work environment[27].

4.3.3 Psychological Value of Outward View

The renovation scheme chose venetian blinds over full blackout curtains, reflecting an emphasis on the value of the view. Through the gaps between the slats, users can still perceive information about the natural rhythm, such as outdoor weather changes and sunrise/sunset. This weak yet continuous visual connection with the outside world is significant for maintaining daytime rhythm perception and alleviating the psychological fatigue from long-term enclosed office work. Studies show that combining daylighting design with shading systems plays an important role in improving the physical and mental health of office environment users[18], and an outward view is one of the key pathways to achieving this goal.

5 Analysis of Human Factors Quality Improvement from the Wind Environment Perspective

5.1 Health Quality Dimension

5.1.1 Enhanced Ventilation Promotes Dilution of Carbon Dioxide and Pollutants

The pre-renovation central corridor layout allowed windows on only one side, with the air inlet and outlet on the same side, failing to form an effective driving pressure difference. According to fluid mechanics principles, ventilation in single-side opening rooms mainly relies on wind pressure turbulent fluctuations or minimal thermal buoyancy differences, resulting in significantly lower air exchange efficiency compared to cross-ventilation. Consequently, carbon dioxide, formaldehyde, and volatile organic compounds generated indoors were difficult to expel promptly. The post-renovation open-plan layout establishes a north-south ventilation corridor. Exterior windows on both north and south sides create a stable wind pressure difference, driving air through the interior in a bulk displacement manner, increasing air change rates several times compared to the original compartmentalized layout. According to the minimum outdoor air requirements for mechanically ventilated spaces in the WELL Building Standard, the natural ventilation rate achieved post-renovation far exceeds the baseline threshold. This can fundamentally control the carbon dioxide concentration in the breathing zone of personnel below 1000 ppm, significantly reducing the risk of drowsiness and headaches caused by carbon dioxide accumulation[28-29]. Controlled experiments have shown that when indoor carbon dioxide concentration rises from approximately 550 ppm to 945 ppm, test subjects' decision-making performance shows an observable decline, whereas enhanced ventilation can effectively reverse this effect by maintaining carbon dioxide concentrations near baseline levels[29].

5.1.2 Shortened Air Age and Prevention of Sick Building Syndrome

Air age refers to the time it takes for fresh air to travel from an inlet to a specific location indoors; it is a key indicator for measuring ventilation effectiveness. A long air age means air stays indoors longer, providing ample time for chemical reactions among pollutants and increasing the possibility of microbial resuspension. Workers in spaces with prolonged air age face a higher risk of illness. The smaller the air age, the fresher the air and the better the air quality[30].

In the post-renovation open-plan layout, the centralized communication area in the middle uses low-height furniture and lightweight partitions, keeping obstacles below desk level. This prevents the formation of airflow shadow zones and recirculation dead zones near the floor, allowing the north-south cross-ventilation to sweep across the occupant activity zone almost unimpeded. Airflow can quickly carry away metabolic exhaust and pollutants exhaled by the human body, compressing local air age to just a few minutes, drastically reducing users' exposure time to non-fresh air. Multiple epidemiological surveys have confirmed that in office spaces with high air age and insufficient ventilation, the incidence of "Sick Building Syndrome" (SBS) symptoms, such as dry eyes, sore throat, headache, and fatigue, is significantly higher. Improving airflow organization and reducing air age can effectively decrease the frequency of these symptoms[28].

5.1.3 Respiratory Safety Assurance in High-Density Occupancy Spaces

The large meeting room on the southwest side is a typical high-density occupancy space. Relying solely on single-side windows or mechanical mixing ventilation cannot solve the problem of localized accumulation of exhaled aerosols within the space. The post-renovation configuration of operable exterior windows on the south and west sides establishes a bidirectional convection ventilation pattern. As the driving wind passes through the room, it not only forms a macroscopic stable unidirectional displacement flow but also generates vortices of certain scales due to obstacles like furniture and human bodies. These vortices promote continuous mixing of air in corners and leeward sides, preventing the formation of high-concentration exposure dead zones. Experimental studies indicate that double-sided ventilation can reduce the residence time of droplets exhaled by an infected person indoors by more than 30%-50%, significantly lowering the infection risk for nearby personnel. Using natural ventilation to continuously dilute and exhaust respiratory pathogens, which are primarily transmitted via aerosols, is currently one of the most convenient and efficient engineering control methods. It is a crucial means of ensuring respiratory safety in high-density occupancy spaces[31].

5.2 Comfort Quality Dimension

5.2.1 Indoor Sensation Closer to Outdoor Natural Wind

The human skin surface is densely populated with thermoreceptors and airflow sensors, highly sensitive to small fluctuations in wind speed. In the original compartmentalized layout, the air was nearly stagnant, leaving users in a steady-state environment lacking dynamic stimuli for extended periods. The cross-ventilation formed in the open-plan layout inherently carries natural fluctuations in various directions and speeds. These random characteristics closely resemble outdoor natural wind, better meeting users' comfort needs. Compared to constant wind, dynamic fluctuating airflow has higher heat dissipation efficiency and provides moderate, non-fatiguing stimulation to skin tactile receptors, avoiding the "adaptation numbness" and uncomfortable draft sensation caused by prolonged constant wind exposure. Therefore, users can maintain a thermally neutral assessment even at higher room temperatures, with the sensations of stuffiness and skin clamminess significantly suppressed, widening the thermal comfort time window[32].

5.2.2 Better Thermal Comfort Experience from Natural Ventilation

Human factors research has repeatedly confirmed that users have a deeper psychological preference for natural ventilation. In naturally ventilated buildings, the acceptable temperature range for the thermal environment is significantly wider than in fully air-conditioned buildings, with higher average thermal comfort votes and lower complaint rates. The mechanism lies in the turbulence spectrum characteristics of natural wind, which are closer to the signal patterns humans are accustomed to during outdoor evolution. The brain interprets this as a "natural cool breeze" rather than an "artificial draft," inducing a stronger sense of pleasure. Simultaneously, as the cross-ventilation carries the unique scent and humidity signals of outdoor fresh air, these multi-sensory cues further reinforce the indoor workers' unique spatial experience. In summary, the improvement in the wind environment not only meets the skin's heat dissipation needs but also matches the human desire for dynamic, fresh, natural air, bringing psychological comfort gains beyond mere physical heat dissipation.

5.2.3 Alleviating Sensory Monotony and Adaptive Degradation in Artificial Environments

Prolonged stays in constant-temperature, still-air air-conditioned rooms lead to adaptive degradation of the body's thermoregulatory functions due to lack of necessary thermal stimulation, manifesting as reduced tolerance to temperature changes and decreased sensitivity of peripheral vasodilation/constriction responses. The original compartmentalized layout lacked noticeable airflow movement. In the post-renovation open-plan layout, the indoor cross-ventilation naturally fluctuates with changing outdoor weather conditions, continuously providing mild thermal stimulation to the skin. This low-frequency, low-intensity physiological stimulus can sustain the activity of the human body's thermoregulatory system, helping to maintain innate thermal adaptability. Moreover, dynamic air movement breaks the monotony of enclosed spaces, alleviating sensory monotony and the feelings of suppression and lethargy prone to occur during prolonged sedentary office work.

5.3 Adaptive Quality Dimension

5.3.1 Differentiated Ventilation Strategy Based on Zonal Air Supply

Ergonomics emphasizes that the optimal environment is not mathematically uniform but matches the dynamic needs of users. After renovation, the building does not apply uniform window opening intensity but implements a precise and reasonable layered ventilation strategy based on the usage characteristics of each sub-space. Based on past usage experience, the large meeting room has high occupancy numbers and dense gathering periods, with instantaneous surges in indoor heat/moisture loads and pollutant generation rates. Therefore, it is equipped with operable windows on two sides, constructing a highly redundant, strong convective air exchange system to maintain good air quality even under such extreme conditions. Small independent offices typically accommodate only a very small number of staff and office equipment, resulting in relatively low heat dissipation and human metabolic emissions. The outdoor airflow required for health ventilation and thermal comfort is much lower than that for the meeting room. Consequently, their ventilation mode is downgraded to a single-side window mode. This achieves the goal of adequate air exchange while avoiding interference with paper placement, noise generation, or unnecessary heat loss in winter caused by excessively strong convection[33]. Matching high-capacity spaces with enhanced ventilation and low-capacity spaces with flexible ventilation is the main design logic for the wind environment in this renovation scheme, fully embodying the adaptive quality of finely coupling environmental resources with human factors needs.

5.3.2 Individual Autonomous Control and Sense of Spatial Control

Research repeatedly confirms that granting users personal control over their micro-environment, even if it does not objectively change physical parameters significantly, can greatly enhance satisfaction and tolerance through psychological mechanisms. The operable single-side window retained in small independent offices is a practical embodiment of this concept. Users can adjust the opening degree and angle of the window sash in real-time, based on their own thermal sensation, clothing level, and personal preferences of the day, creating a personalized airflow micro-environment.

Within the building's spatial configuration, the single-side operable exterior window in small independent office units serves as a typical implementation of the design concept of controllable human settlement micro-environments. This window form grants users full behavioral autonomy. Personnel can flexibly and autonomously adjust the window opening extent and tilt angle based on multiple personalized factors such as their real-time thermal comfort perception, seasonal clothing insulation level, individual metabolic differences, and daily subjective preferences. Through fine-tuned natural ventilation regulation, they can shape an exclusive airflow field and localized microclimate zone tailored to personal comfort needs, thereby weakening the rigid discomfort caused by standardized air-conditioned environments and achieving a dual balance of comfort in both physical environment and psychological perception[33].

6 Conclusions and Outlook

6.1 Conclusions

This study, through investigating the human factors quality improvement effects following the energy-saving renovation of an office building in Shanghai, draws the following conclusions:

(1) After the luminous environment renovation, annual lighting energy consumption was reduced by 18,500 yuan, down to 15% of the pre-renovation level. On sunny days, the daylight illuminance at all workstations in the open-plan space can reach over 300 lx without artificial lighting, requiring lighting only after 17:00. On overcast days, illuminance in the main space drops below 300 lx after 15:00, with some rooms needing supplemental light only after 17:00. As long as the daylight illuminance is above 50 lx, activating only 50% of the lighting power can raise the workstation illuminance to over 350 lx. This shows that even under the weakest natural light conditions, only half the lighting power is needed to meet usage requirements.

(2) Based on the overall natural ventilation wind speed contour map, the post-renovation building’s overall natural ventilation effect is significantly better than before. Using CFD simulation and thermal comfort calculations, combined with Shanghai's typical meteorological year data, the annual air conditioning on/off days and corresponding energy consumption were calculated. Pre-renovation, due to poor ventilation, cooling was needed when the outdoor daily average temperature exceeded 26 ℃, with only 30 days a year without AC. Post-renovation, thermal comfort improved significantly, increasing the number of days without mechanical cooling to 90 days per year. The energy analysis indicates that the annual operating energy consumption of the air conditioning system decreased by 16.4%, equivalent to a saving of 6,176 yuan in electricity costs.

(3) The luminous environment renovation scheme improved illuminance levels and luminance distribution, effectively controlled glare, enhanced visual comfort, and alleviated visual fatigue. Natural light regulates workers' circadian rhythms, and the renovation improved the building's utilization of daylight, greatly benefiting the physiological health of the staff. The ceiling-free design increased the sense of spaciousness and environmental control, benefiting the psychological health of the staff.

(4) The wind environment renovation scheme resulted in good natural ventilation, aiding the dilution of carbon dioxide and pollutants, shortening air age, effectively preventing Sick Building Syndrome, and providing a healthier working environment. Post-renovation, the indoor sensation felt by occupants is closer to outdoor natural wind, offering a better thermal comfort experience and alleviating the sensory monotony and adaptive degradation associated with artificial environments.

6.2 Outlook

This renovation scheme has been completed and implemented, and facts have proven its significant energy-saving effects. After the energy-saving renovation, users have gained a healthier and more comfortable work experience. However, it is still necessary to widely gather user feedback to propose even better measures and ideas for building renovation work.

With the progression of time, the concept of green and low-carbon practices is gradually gaining public acceptance. Building energy-saving renovation projects have broad development prospects. In the future, more and more diverse buildings will undergo energy-saving renovations. Before carrying out such renovations, extensive simulation and analysis—similar to the building planning and design phases—are needed to achieve better renovation outcomes.

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