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Empirical research on vertical greening and energy saving technology in the range of architectural boundaries

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Abstract: The practical application effect of ecological energy-saving technologies on the building boundary areas was researched and analyzed using observation data from the Tus-Design headquarters office building renovation project collected over a period of ten years. In order to compare the growth of various plants in various orientations over a 10-year period and the changes in the plants throughout the year, the characteristics of three-dimensional greenery in the building's four orientations were first investigated. The study finds that, in order to maximize shading performance and energy-saving effects, plant selection should take into account both building orientation and plant characteristics. Deciduous and evergreen plants should also be used together. After measuring the energy-saving temperatures of the vertical ecosystem, double-glazed curtain wall system, and regular glass curtain wall system, the data analysis shows that the vertical ecosystem has a better ability to save energy when put to use. The results of the study show that the three-dimensional greening system has a more pronounced advantage when the outside temperature is above about 27 ℃, especially on the west side. When the temperature is lower than 25 ℃, its energy-saving advantage is less pronounced.

Key words: green building; ecological energy-saving technology; vertical ecosystem; sun-shading; building renovation

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In accordance with China's national peak carbon dioxide emissions goal in the 2030 and 2060 carbon neutrality pledge, the effective control of architectural carbon emissions has become a new tendency in green architecture development. The full life circle of architectural carbon emissions involves seven steps, namely, building material production, building material transportation, building construction, building operation, building maintenance, building disassembly, and waste disposal[1]. As a whole, the carbon footprint of building operations plays a leading role among the seven steps. Therefore, choosing appropriate ecological energy-saving technologies can not only reduce carbon emissions in production, transportation, and construction steps but also play a significant role in the subsequent operation, maintenance steps, and other potentially relevant aspects.

On the one hand, ecological energy-saving technologies can create a comfortable environment for users and enhance the harmonious interaction between humans and nature while achieving effective energy conservation. Hence, ecological green architecture has become one of the most important green building design methods in recent years. On the other hand, the growth of plants can be influenced by a number of elements, such as regional climates and building orientations. The final building may fall short of the expected energy-saving performance due to improper selection or combination of plants or poor maintenance. In addition, excessive natural lighting will cause glare and high energy consumption. Incorrect natural ventilation patterns may also cause partially excessive air flow and poor comfort. Thus, vertical climbing plant species and allocation mode, when properly designed, are beneficial to building cooling, humidification, carbon sequestration, and oxygen release and could finally contribute to energy conservation[2]. The Tus-Design headquarters office building renovation project is a typical example of a green building in the hot summer and cold winter areas in China, and as such, it has received the green building assessment standard three-star operation label. To sum up, the purpose of this study is to examine the actual energy-saving performance of ecological green buildings and summarize the design procedures and the advantages and disadvantages of ecological energy-saving technologies based on the 10-year continuous observation data on the Tus-Design headquarters office building renovation project.

1 Green Design Measures in the Range of Architectural Boundaries of the Tus-Design Headquarters Building

The Tus-Design headquarters office building is located in Suzhou and was renovated from an old factory build-

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ing. The renovation project was completed and put into use in 2010[3]. In this project, some ecological reconstructive measures were added to the range of the architectural boundaries for low-technology and high-efficiency passive energy conservation, including better natural lighting, natural ventilation, and ecological shading[4]. One year after the project's construction, it received the three-star operation label of the green building assessment standard (see Fig. 1 offered by Tus-Design Group Co., Ltd.).

Fig. 1 Photos of the Tus-Design headquarters office building. (a) Southeast corner of the office building; (b) Main east entrance of the office building; (c) West facade of the office building; (d) West facade of the office building; (e) South facade of the office building; (f) East facade of the office building

1.1 Ecological design on the building facade

This building is mainly two-story and partially four-story in height and serves as an office space, a meeting space, a canteen, and other auxiliary facilities after the renovation. The overall floorage is 11 000 m^2. On the four facades of the building, a comprehensive vertical ecosystem, which combines vertical greening and a sunshading structure, was designed for energy conservation. Based on research, the use of vertical greening in the building envelope is an effective passive strategy to reduce building energy consumption and reduce the urban heat island effect[5-8]. In addition, there are several energy-saving measures on the facade, such as the double-glazed curtain wall system and electric external shading system (see Fig. 2).

Arbors, shrubs, climbing plants, and veranda frames constitute the vertical ecosystem. For the investigation, different kinds of climbing plants have been set on each side of the building. Chinaberry trees, sweet-scented osmanthus trees, crape myrtles, and other arbors and shrubs have been planted near the ground floor of the building. On the 1st floor, there are evergreen shrubs, such as China rose; evergreen subereous shrubs, such as trailing abutilon; and evergreen climbing plants, such as ivies. Trailing abutilon has a slender and much-branched lithe stem. It is similar to ivies, hanging and shading the direct sunlight. Moreover, trailing abutilon and China rose are perpetual flower trees that have high ornamental values (see Fig. 3).

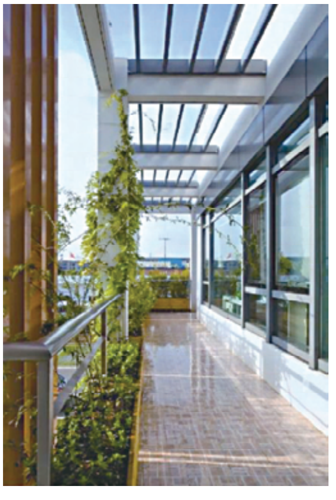
Fig. 2 Plants on the 1st floor

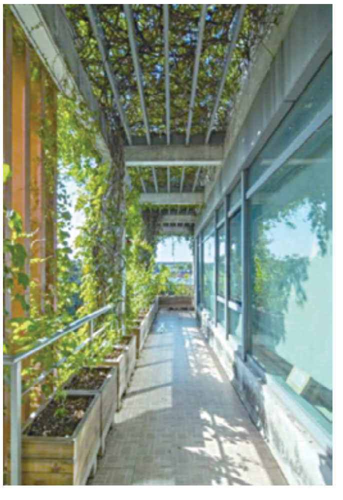
Fig. 3 Top view of the Tus-Design headquarters office building

In contrast, Chinaberry trees, a kind of tall arbor, are planted to the west of the building. The Chinaberry trees have grown up to three-story tall and can effectively shade the summer sunlight on the west side (see Fig. 4). Crape myrtles are planted on the south side of the ground floor, and sweet osmanthus are planted to the east of the building. They can help shade the direct sunlight on the ground floor, combined with the verandas. On the south side of the 1st floor, Chinese wisteria and *Mucuna sempervirens* are planted near the sunlight-shading veranda frames as a vertical shading system (see Fig. 5). The vertical ecosystem, formed by trees, shrubs, climbing plants, and hanging plants, can provide effective shading performance and high landscape quality.

(a) (b)

Fig. 4 Photos taken in different periods. (a) Newly planted Chinaberry trees to the west of the building in 2010; (b) Tall and thick Chinaberry trees to the west of the building in 2015





(a) (b) (c)

Fig. 5 Veranda with a vertical ecosystem. (a) Section of the vertical ecosystem on the south side; (b) South veranda on the 1st floor in 2010; (c) South veranda on the 1st floor in 2019

The building renovation project is in Suzhou. Suzhou is a city in the north subtropical humid monsoon climate region, having hot summers and cold winters. The climates in Suzhou are warm, humid, and rainy. In Suzhou, there are four distinctive seasons. Thus, it has rich plant species, which are listed in Tab. 1.

Tab. 1 Species of the plants on site

No.	Scientific name (common name)	Family & genus	Description	Habits	Location on site
1	*Wisteria sinensis* (Chinese wisteria)	Fabaceae, Wisteria	Deciduous lianas, large and showy flowers, charming fragrance, thick vine, sturdy and strong climbers, dense branches and leaves; flowering phase: from April to May	Heliophilous plants, slightly shade-enduring; like warm and humid climates, slightly hardy, water-based stain resistance, and strong adaptability to different kinds of soil	South facade
2	*Campsis grandiflora*	Bignoniaceae, Campsis	Deciduous woody lianas, large flowers, climb up tree stems and walls; flowering phase: from May to August	Like warm and sunny climates, grow well in fecund, moist, and weak acidic soil with a good drainage effect	West facade and east facade
3	*Mucuna sempervirens*	Fabaceae, Mucuna	Evergreen woody lianas, compound leaves	Comparatively fast-growing, strong and thick stems and thick leaves	South facade and west facade
4	*Hedera nepalensis var. Sinensis*(Ivy)	Araliaceae, Hedera	Perennial evergreen climbing shrubs, aerial root	Fast-growing, like warm climates, hardy	West facade
5	*Parthenocissus tricuspidata* (Boston ivy)	Vitaceae, Parthenocissus	Deciduous woody lianas, sturdy-dependent	Strong adaptability, like sunless and moist environments, are not afraid of hard light, hardy, drought resistance, barren soil resistance, and adaptive to a variety of climates	Inner courtyard
6	*Abutilon megapotamicum* (Trailing abutilon)	Malvaceae, Abutilon	Evergreen lithe woody shrubs, green leaves, flower all year round, red lantern-shaped flowers	Like warm climates, intolerant of the cold weather	South facade, west facade, and east facade
7	*Melia azedarach* (Chinaberry tree)	Meliaceae, Melia	Trees to 10 m tall, deciduous, branches spreading, flowers fragrant, petals lilac-colored; flowering phrase: from April to May; fruit phase: from October to December	Pay little emphasis to soil, like warm and moist climates, hardy, and strong adaptability	West facade
8	*Osmanthus fragrans* (Sweet osmanthus)	Oleaceae, Osmanthus	Evergreen shrubs, 3 to 5 m tall, tall up to 18 meters maximum, extremely fragrant flowers; flowering phase: from September to early October	Like warm and humid climates, heat-resistant and cold-resistant	East facade
9	*Lagerstroemia indica*(Crape myrtle)	Lythraceae, Lagerstroemia	Deciduous shrubs, tall up to 7 m, various colored flowers; flowering phase: from June to September	Like warm and humid climates, heliophilous, slight shade-enduring, strong stain resistance, have strong resistance to sulfur dioxide, hydrogen fluoride and chlorine	South facade

The selection of plants was considered together with the building orientations and energy-saving requirements. Based on the continuous observation data, the actual energy-saving effect is relatively remarkable.

1.2 Ecological design on the rooftop

The traditional insulated roof of the original building had been used for ten years before the renovation. The insulation of the original roof was actually barely satisfactory. However, it would raise the cost of time and money if most of the roof materials were replaced. Thus, plants were used for shading and insulation during the roof energy-saving reconstruction process. To reasonably distribute the horizontal loads, large planting slots were set on the columns and beams, with frames for climbing plants above. Various crops, such as towel gourds and bottle gourds, were planted near the frames following the seasons. The crops can provide food materials for the canteen, performing as a part of the roof shading system at the same time.

1.3 Ecological design on the inner courtyards, patios, and skylights

Before the renovation, the original building was a rectangular factory building, 95 m from north to south and 75 m from east to west. The large volume and depth of the building can cause poor natural lighting and natural ventilation for office use. During the renovation, an L-shape and Z-shape inner courtyards were added to enlarge the perimeter of the building's climate boundary.

The new courtyards bring plenty of lighting and ventilation to almost every room in the building. Indoor environment quality (IEQ) can be effectively improved by achieving better air convection in each room through the reasonably arranged inner courtyard. It has been proved that IEQ directly affects the comfort and health of indoor users[9]. Compared with adsorption and chemical removal methods, natural ventilation is a more effective and convenient way to remove indoor air pollution and improve indoor air quality[10]. It has also been proven in the past three years since COVID-19 appeared that adequate natural ventilation improves the indoor environment and the physical and mental health of space users.

In courtyards, Boston ivies on walls can not only reduce the thermal radiation on the external walls in summer but also decrease office users' visual fatigue. As a result, thick and flourished Boston ivies attract birds and become their habitats each summer, which is not expected but pleasing (see Figs. 6 and 7).

(a) (b)

Fig. 6 Inner courtyards (offered by Tus-Design Group Co., Ltd). (a) View toward one side of the L-shape inner courtyard; (b) Middle of the Z-shape inner courtyard

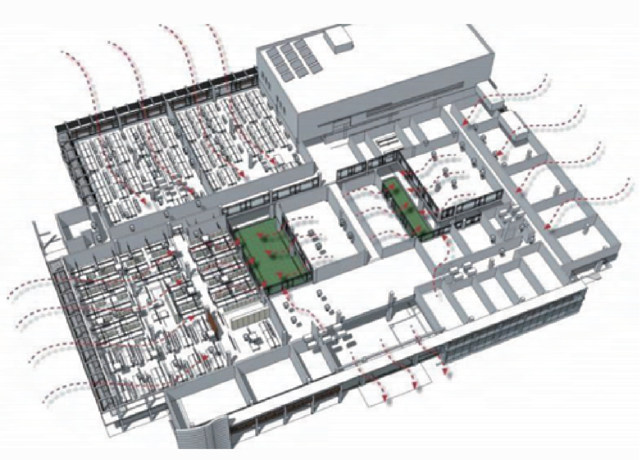


Fig. 7 L-shape and Z-shape inner courtyards added to enlarge the perimeter of the building climate boundary

The building roof is the fifth elevation of the architectural boundaries. To meet the requirements, electric opening skylights and light pipes were added to the roof, optimizing the natural light and ventilation performance of the building top. In particular, for the exhibition hall on the 1st floor, the east external windows, inner courtyard to the west, and electric opening skylights and light pipes above constitute the comprehensive natural lighting and ventilation system around the building. Except for bad cloudy weather, artificial lights are not needed in the exhibition hall during the daytime (see Figs. 8 to 10). Based on the actual testing data, when the exterior illuminance was 62 963 lx, during sunny days, the average interior

Fig. 8 Exhibition hall on the 1st floor

Fig. 9 Section of the exhibition hall

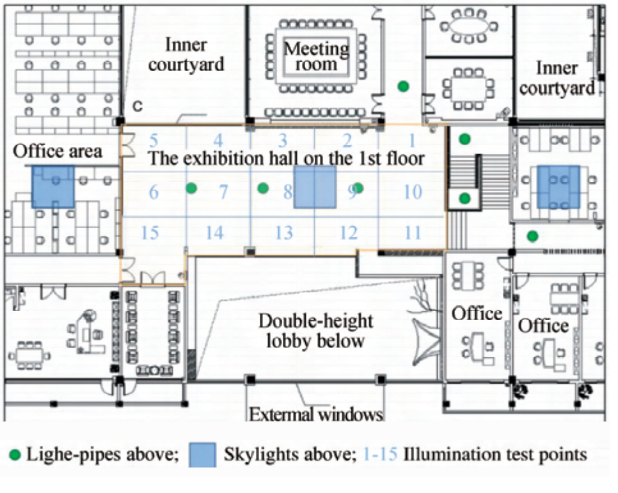


Fig. 10 Plan of the exhibition hall

illuminance was 526.8 lx (see Tab. 2). Moreover, when the exterior illuminance was 17 980 lx, overcast outside, the average interior illuminance was 233.2 lx. According to the *standard for lighting design of buildings* (GB 50034—2013), the standard value of the illuminance in a permanent exhibition hall is 200 lx. Thus, the lighting system in the exhibition hall on the 1st floor can provide satisfactory illumination on sunny and overcast days.

Tab. 2 The illumination test results for the indoor public space of the Tus-Design headquarters office building

Test point	Sunny day illuminance/lx	Cloudy day illuminance/lx
Outdoor test point	62 963.0	17 980.0
Indoor test point 1	103.6	47.0
Indoor test point 2	197.0	68.5
Indoor test point 3	296.0	151.5
Indoor test point 4	1 823.4	945.0
Indoor test point 5	1 206.5	880.0
Indoor test point 6	385.6	86.0
Indoor test point 7	672.3	180.0
Indoor test point 8	767.5	252.0
Indoor test point 9	988.9	375.5
Indoor test point 10	275.5	50.5
Indoor test point 11	175.4	40.5
Indoor test point 12	278.3	121.4
Indoor test point 13	290.0	120.8
Indoor test point 14	276.6	120.7
Indoor test point 15	164.9	58.6
Indoor average	526.8	233.2

Notes: 1) The indoor test points are 0.75 m above the floor and the outdoor test point is on the ground level. 2) Test time is 11:45 a. m. to 12:45 p. m. 3) Standard value of the illuminance in a permanent exhibition hall is 200 lx in *Standard for lighting design of buildings* (GB 50034—2013). Standard value of the natural illumination in an exhibition hall is 300 lx in *Standard for the daylighting design of buildings*(GB 50033—2013).

1.4 "Five senses" in the ecological designs in the range of architectural boundaries

In the range of architectural boundaries, ecological designs provide a rich experience of the five senses, namely, smell, vision, touch, taste, and hearing, for users. The five senses are the most essential and direct mediums by which people experience the world. The ecological designs in the project built an environment abundant with biodiversity. In the environment mentioned above, birds' tweets and the fragrance of flowers in different seasons bring multiple smell and hearing experiences. Luxuriant plants serve ecological visual effects, which can effectively relieve eyestrain after working long hours at a desk. Moreover, the planting areas on the rooftop can provide the canteen with fresh vegetables and allow the staff to eat fresh produce.

Human bodies have clear senses of touch and vision under adequate natural lighting in ecological systems. Mohamed Boubekri from the Illinois Institute of Technology briefly states in his book *Daylighting, architecture and health: building design strategies* that "Because we are dependent on light for perception, it is natural that we should be psychologically affected by it." In his book, it is also mentioned that "most people prefer natural lighting and feel better under daylight conditions than under artificial lighting"[11]. Thus, there is a causal relationship between the interior environment, which has enough natural light, and human health. All-around daylight guidance by lighting through facades, inner courtyards, skylights, and light pipes can bring users a direct vision and touch experience. For example, exposure to winter sunlight induces natural happiness. Furthermore, an excellent lighting design will not only focus on guiding the light but also take light control into account. The directions where the light is coming from and the distribution of the light should both be taken under control. Too much light could easily cause an increase in the temperature, especially in summer. According to this research, higher temperatures will increase negative mental health outcomes, whereas lower temperatures will reduce mental health problems [12]. For this reason, it is particularly important to take lighting and shading into consideration together properly.

2 Tracking and Comparison of the Plants' Growth and Change in the Vertical Ecosystem

On the facade of the office buildings, vertical ecosystems are designed for energy conservation. This building is used as the Tus-Design Group's own office space. Research Group I has tracked and compared the vertical ecosystem for a decade after the project was finished (see Fig. 11). The actual energy-saving effect of the vertical ecosystem will be analyzed and discussed in four aspects.

2.1 Contrastive analysis of the growth and performance of different plants on the same side of the building

The plants on site have been growing since May 2010. We take the *M. sempervirens* and Chinese wisteria on the south side as an example. In the past ten years, they grew in similar environments and the same ground floor soil without a basement below. During the same growth period, the evergreen *M. sempervirens* grew faster than the Chinese wisteria (see Fig. 12). They also have larger leaves and stouter branches, which help provide better shading performance for the building. *M. sempervirens* have deep purple flowers and are fragrance-free but have a slightly fishy smell. Thus, their ornamental experience is insufficient. By comparison, the Chinese wisteria has more beautiful flowers and higher ornamental value during the blossom season. It took 2 to 3 years for them to grow till they could provide essential shading effects in summer (see Fig. 13). However, the Chinese wisteria and *Campsis grandiflora* are deciduous lianas, lack sun-shading ability in winter, and have staggered blossom seasons. Chinese wisteria blooms in spring, whereas *C. grandiflora* blooms in summer. Thus, they can coordinate with each other for better ornamental effects.

Fig. 11 Vertical ecosystem a decade after the project was finished. (a) East facade in 2009 (before the renovation); (b) East facade in 2010 (after the renovation); (c) East facade in 2015; (d) East facade in 2020

Fig. 12 Growth contrast photos of *M. sempervirens* and Chinese wisteria on the south facade (taken in the same period). (a) Growth of *M. sempervirens* on the south facade; (b) Growth of the Chinese wisteria on the south facade

Fig. 13 Growth of *C. grandiflora* on the east facade. (a) East facade in 2009 (before the renovation); (b) East facade in 2010 (after the renovation); (c) East facade in 2012 (*C. grandiflora* climbed up to the 1st floor); (d) East facade in 2014 (*C. grandiflora* climbed up to the rooftop)

2.2 Contrastive analysis of the growth and performance of the same kind of plant on different sides of the building

Growth orientations may affect the performance of the same kind of plant, for example, *C. grandiflora*. They are mainly planted on the east and west sides of the office building. On the southeast side, *C. grandiflora* could have abundant sunlight. Another control group of *C. grandiflora* was planted on the north side, where the sunlight is weaker than that on the southeast side. Suzhou has distinct monsoon changes. The wind blows from the northwest in winter and blows from the southeast in summer. As a result, the cold wind always inhibits the healthy growth of *C. grandiflora* on the northwest side of the building. Furthermore, the wind in summer usually cools *C. grandiflora* on the southeast side and helps ventilation. After years of growth, *C. grandiflora* on the southeast side grows much better than the others on the northwest side and has a better shading performance. The control group on the northwest side is scattered and cannot provide enough sun-shading.

2.3 Plants' growth in four seasons

To study the climbing plants' seasonal change, photos of the building facades were taken from the same angles at the beginning of each month in their 10th year of growth. The photos showed the significant seasonal change differences between the Chinese wisteria, *M. sempervirens*, *C. grandiflora*, and Boston ivies (see Fig. 14). Based on the observation data, taking deciduous as an example, the Chinese wisteria usually begins to shed leaves around the middle of December, sprouts in early March, takes shape in April, and has an excellent sun-shading performance in May. In particular, the Chinese wisteria on the southeast corner of the building could be desirable and flourish in April at the earliest in a year. Due to the distinct seasons in Suzhou, the Chinese wisteria has high ornamental value throughout the blossom season. However, they are not ornamental enough during fall. *M. sempervirens* are evergreen and usually more luxuriant and provide better sun-shading in summer. Thus, it is necessary to plant plants with different characteristics and habits together to make them play a coordinating role and obtain ideal effects (see Fig. 15).

2.4 Biodiversity change after the renovation[13]

Before the renovation, the site was a heavy industry factory block with simple plant species, which are mainly lawn and camphor trees. After the renovation, the rich plant species include over 20 kinds of large arbors, such as camphor trees, Zelkova trees, and Chinaberry trees; over 20 kinds of large shrubs, such as sweet osmanthus, banana shrubs, and red maples; more than 10 kinds of undershrubs, such as *Photinia serrulata*; and over 30 kinds of ground covers, such as *Rosa chinensis* and *Rosa gallica* (see Fig. 16). After years of continuous observation, it is proven that the plant species help improve the natural environment around the site by attracting animals and insects gradually. In the first years, there were mainly sparrows on site. In subsequent years, other kinds of birds, such as hoopoes and Chinese bulbuls, appeared on the site. Beehives even appeared below the flower frames in the rooftop garden.

(a)

(b)

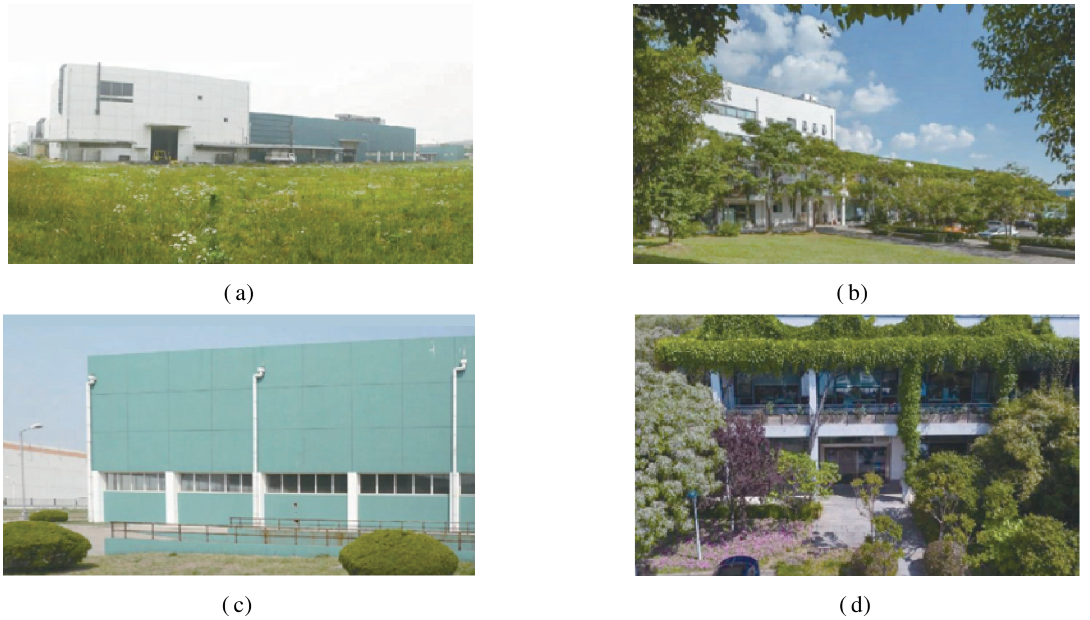
Fig. 14 Growth contrast photos of *C. grandiflora*, deciduous lianas, on the east facade (taken in the same year's summer and winter). (a) *C. grandiflora* on the 1st floor after shedding leaves period in winter; (b) Thick and luxuriant *C. grandiflora* on the 1st floor in summer

2.5 Summary

The ecological measures in the Tus-Design Headquarters office building renovation project not only enrich the biodiversity on the site but also have a remarkable role in energy-saving effects. In the vertical ecosystem of the project, arbors, shrubs, and lianas were collocated, and evergreen plants were planted together with deciduous plants, considered on the basis of the sun-shading requirements of the building's different facades.

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Fig. 15 Growth of *C. grandiflora* and Boston ivies to the south of the building in each month of the year. (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November; (l) December



(a) (b) (c) (d)

Fig. 16 Contrasting photos of the plant species in the building before and after the renovation. (a) Lack of plant species on the site before the renovation; (b) Rich plant species on the west facade after the renovation; (c) Lack of plants to the south of the building before the renovation; (d) Rich plant species to the south of the building after the renovation

The actual usage situation denoted that the sun-shading performance of the vertical ecosystem is excellent during summer. However, during winter, the Chinese wisteria and crape myrtles on the southeast side are deciduous, which causes strong sunlight on the southeast facade. Moreover, due to the low solar altitude during winter, improper natural lighting will cause glare in the office space and make users uncomfortable. By contrast, *M. sempervirens* on the southwest side and the sweet osmanthus on the east side are evergreen plants that have good sun-shading effects and can avoid glare problems. Therefore, planting evergreen and deciduous plants together has a high ornamental value and sun-shading value.

3 Contrastive Analysis of the Measurement Data in Different Areas of the Building Facades

The double-glazing curtain wall[14], electric external shading, low-E insulating glass curtain wall system, and other facade energy-saving systems are also used in the building envelope of the Tus-Design headquarters office building, apart from the vertical ecosystem. During their use, their actual effects were analyzed based on close and constant observations and a large amount of data. In the following subsections, the actual effects of the vertical ecosystem and the other energy-saving systems will be discussed and compared with one another (see Fig. 17).

To further verify the energy efficiency of the vertical ecosystem, the measurement data of the building envelope temperature of different areas on the building facade were recorded and compared. As the measurement accuracy may be influenced by air conditioners' setting temperature, room sizes, users' habitats, and other possible factors, the surface temperature measurements were performed simultaneously in different building envelope areas. Under the same kind of building envelope areas during summer, with the same environment temperature, the lower the envelope temperature is, the higher the sunshade efficiency and the better the energy-saving effect.

Temperature measurements were taken during June when the temperature difference between day and night was large. The highest temperature on average in June was 31 ℃, and the averagelowest temperature was 23 ℃. A group of typical data in four consecutive days was taken forward for the data analysis. During the test, the maximum outdoor temperature was 33 ℃, and the minimum was 20 ℃. The weather during the study period was cloudy. The detection instruments used in the test were temperature and humidity self-meters and contact thermometers.

3.1 Contrastive analysis of the measurement data of different areas on the east building facade

The east side of the office building was designed with a double-glazed curtain wall energy-saving system and a veranda-type vertical ecosystem as a control group (see Fig. 18). The deciduous climbing rattan plant *C. grandiflora* was selected for vertical greening with the evergreen shrub plant sweet osmanthus. A box-type double-glazed curtain wall system was adopted for the double-layer curtain wall. The actual results were compared as follows:

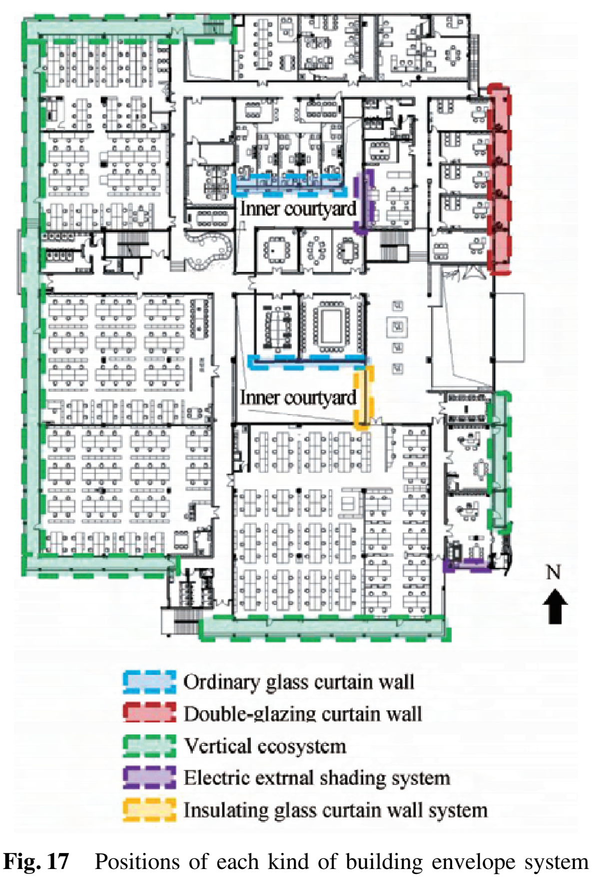
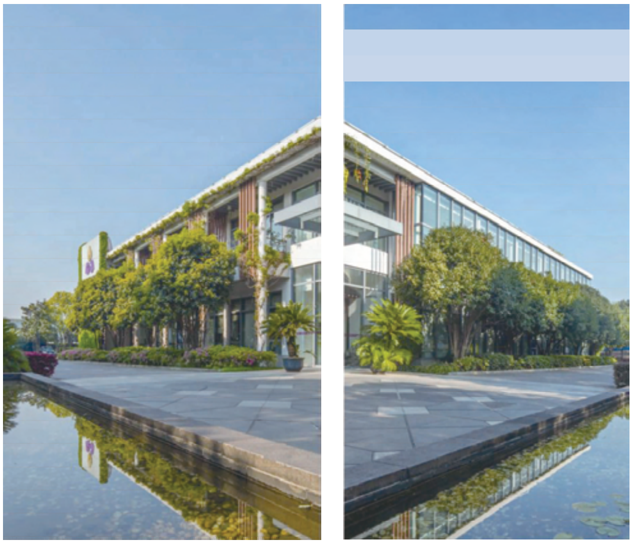


Fig. 17 Positions of each kind of building envelope system



(a) (b)

Fig. 18 Two types of areas on the east building facade. (a) Veranda-type vertical ecosystem on the east facade; (b) Double-glazed curtain wall on the east facade

3.1.1 Architectural appearance

The facade of the double-glazed curtain wall system is simple and lively, and the vertical ecosystem is ecological.

3.1.2 Interior space

The view through the double-glazed curtain wall system is more blocked, and the field of vision is not wide enough. The 2.1-m-wide middle passage space is not fully utilized due to the lack of an air conditioning system and insufficient comfort. The vertical ecosystem has a good view, from the interior to the outside, with a rich natural landscape. The 1.6-m-wide greening corridor provides a comfortable visual environment to the users and also serves as a resting place after work, with a high utilization rate (see Figs. 19 and 20).

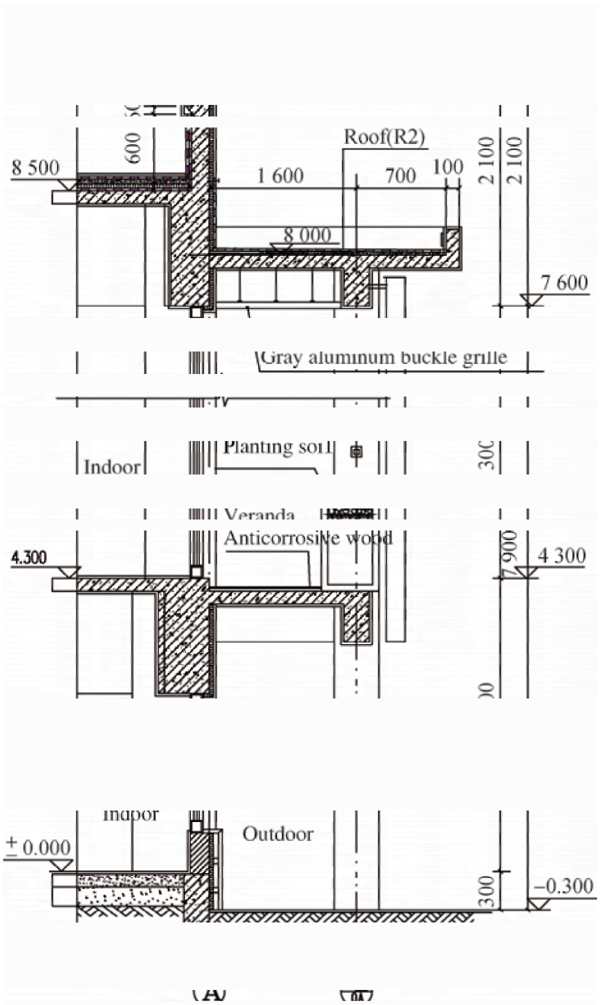


Fig. 19 Details of the veranda-type vertical ecosystem (unit: m)

Imitation wood vertical shading is set outside the east and west corridors of the building to block direct sunlight in the morning and evening. The bottom layer is sheltered from the western sun by planting large trees. The plants in the corridor planting slots can also climb to the upper part of the building along the vertical shutters to strengthen the ecological shading effect.

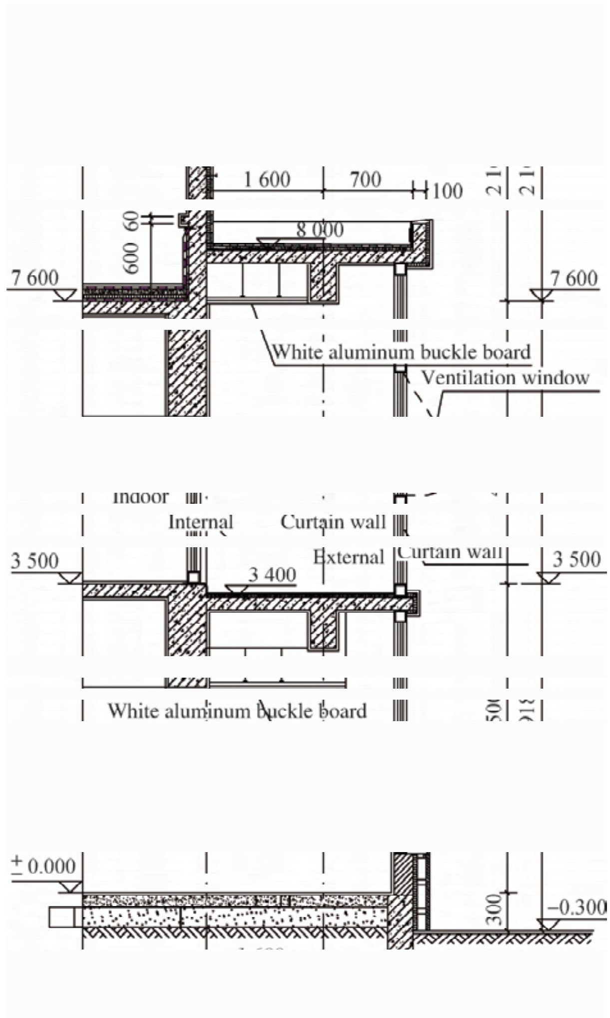


Fig. 20 Detail of the double-glazed curtain wall system (unit: m)

For a comparative study, in rooms that cannot achieve ecological shading in the east corridor of the building, the balcony is closed with low-E-coated insulating glass windows to form a double-layer curtain wall system to reduce heat radiation during summer and provide thermal insulation during winter. The maintenance structure of the outer wall of the building adopts a white high reflection coating to enhance the energy-saving effect.

3.1.3 Use and maintenance

Manual ventilation windows are adopted in the double-glazed curtain wall system, which has high requirements for the energy-saving knowledge that users need to master. Users should pay attention to the changes in the outdoor temperature and how to open or close the ventilation window or other equipment in time to achieve an energy-saving effect. For example, in summer, if the ventilation window is not opened in time to exhaust the hot air in the double-glazed curtain wall, it will not achieve the effect of energy conservation and comfort use, and sometimes it is even worse. The middle passage of the double-glazed curtain wall system belongs to the room-temperature regulating space, with low comfort and a low actual utilization rate of the space. The later maintenance of vertical ecosystems is mainly plant growth maintenance. Because the office building has been operating for ten years, the main trees, shrubs, and climbing plants are directly planted in the soil on the first floor, which is more favorable for plant growth. Most of the buildings are two-story-high structures, and it is more convenient to prune and maintain the plants. Therefore, the overall operation and maintenance of the vertical ecosystem in the office building cost less.

3.1.4 Data analysis

From the measurement data, three areas, namely, the veranda with the vertical ecosystem, the corridor of the double-glazed curtain wall system, and the common external window in the east facade, were selected for the temperature comparison analysis. Based on the analysis results (see Figs. 21 and 22), the corridor temperature in the double-glazed curtain wall system is significantly higher than the other two groups of comparative data, with an average of 2.6 ℃ higher than the corridor with the vertical ecosystem and maximum temperature difference of 11.4 ℃. From the chart data, in cloudy weather, the temperature curve is relatively gentle, whereas on the fourth morning, because the measured area is located in the east, the direct hard sunlight from the low morning sun made the temperature rise abruptly. However, as the sun rises, the temperature of the veranda with a vertical ecosystem immediately drops after the sunlight is blocked by vertical greening. The temperature of the middle corridor with the double-glazed curtain wall system falls more slowly. It was not until sunset that the temperature was basically close to that of the veranda with a vertical ecosystem. The outdoor temperature rapidly decreased after sunset, whereas the temperature in the middle corridor of the double-glazed curtain wall slowly decreased, keeping above 26 ℃. Compared with the veranda temperature of the east vertical ecosystem and the east outdoor temperature, when the temperature is above 27 ℃, the temperature difference between them is more obvious. The higher the outdoor temperature is, the greater the temperature difference would be, which indicates that the vertical

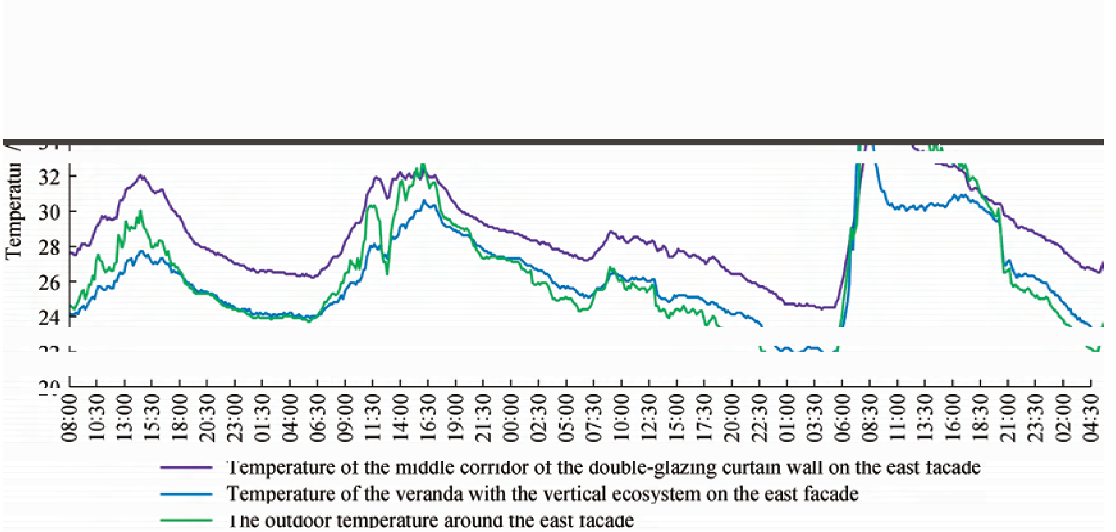


Fig. 21 Temperature on the east facade (4 consecutive days)

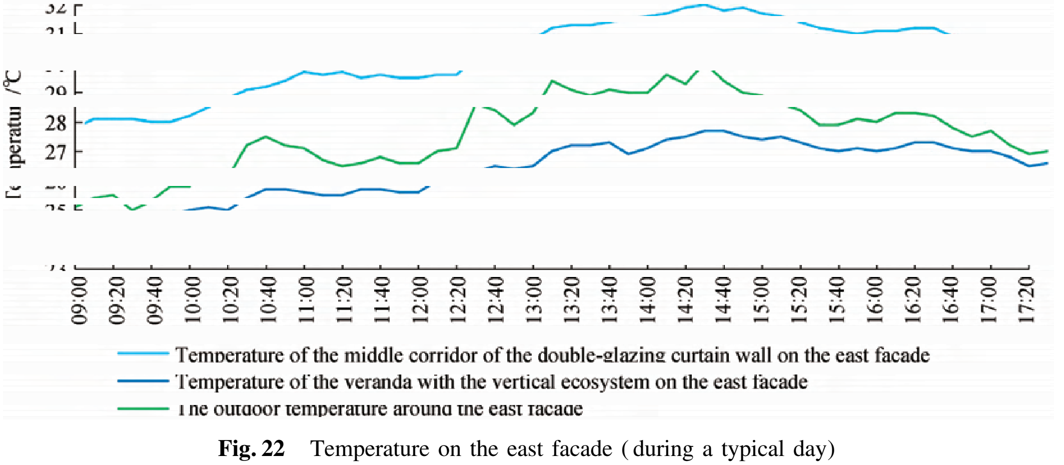


Fig. 22 Temperature on the east facade (during a typical day)

ecosystem has a better energy-saving effect in hot summer. In addition, the higher the outdoor temperature is, the more obvious the energy-saving effect would be under the vertical ecosystem.

3.2 Contrastive analysis of measurement data of different types of areas on the south building facade

Through the measurement data, three areas of the south building facade, i. e., the veranda with a vertical ecosystem, external window facing the inner courtyard, and ordinary external window (not facing the inner courtyard and without a shading system), were selected for temperature comparison analysis. According to the results (see Tab. 3 and Figs. 23 and 24), the overall temperature of the veranda with the vertical ecosystem is lower than that of the ordinary external window, and the temperature difference reaches a peak around 14:00. The temperature difference between the veranda with the vertical ecosystem and the outside temperature of the ordinary external window was analyzed in more detail for 6 h with higher temperatures during the daytime (see Tab. 3). As shown in the average temperature difference in four days, when the outdoor temperature is below 25 ℃, the temperature difference between the two areas is very small. The higher the outdoor temperature, the greater the temperature difference is. When the outdoor temperature was above 31 ℃, the average temperature difference reached 4.89 ℃. Hence, the higher the temperature, the more obvious the energy-saving effect of the veranda of the vertical ecosystem. Based on the charts, the temperature on the outside of the external window facing the inner courtyard is slightly lower than that of the common window (not facing the inner courtyard and without a shading system) but higher than that in the vertical ecosystem veranda area. This finding indicates that the trees in the inner courtyard have a certain effect on shading, but not as obvious as the vertical ecosystem along the south veranda.

Tab. 3 Outdoor temperature and measured point temperature difference ℃

Days	Temperature ranges in 6 h each day	Difference between the average temperatures on the veranda area with a vertical ecosystem and out-of-the-ordinary external window	Weather
Day 1	26.8-30.9	1.20	Cloudy
Day 2	29.0-34.9	2.38	Cloudy
Day 3	24.7-25.9	0.26	Light rain to cloudy
Day 4	31.5-37.1	4.89	Sunny to cloudy

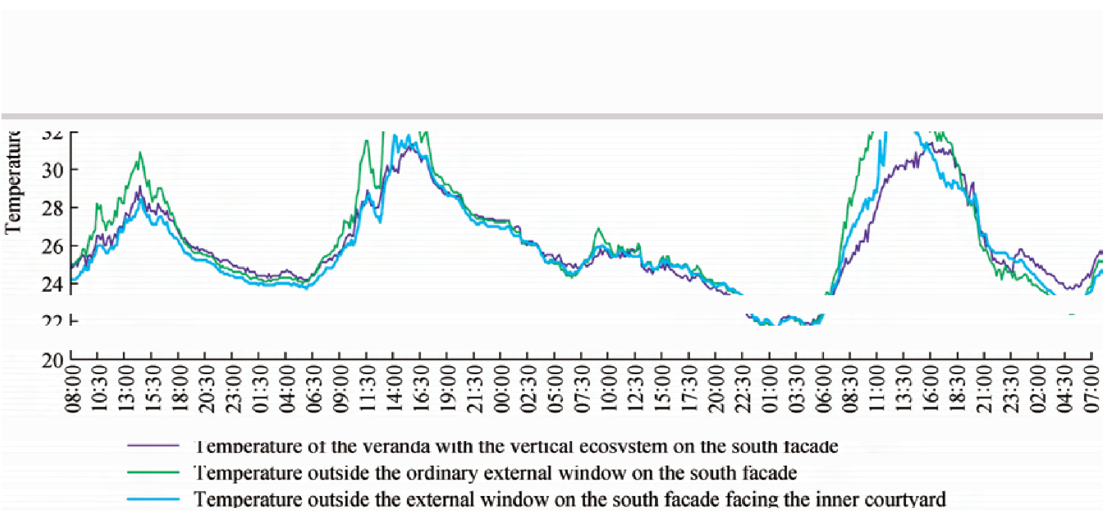


Fig. 23 Temperature on the south facade (4 consecutive days)

3.3 Contrastive analysis of the measurement data of different types of areas on the south building facade

In the energy-saving design of the peripheral protective structure of the building transformation, electric external sunshade blinds are locally installed on the west facade. From the actual use, the advantage of the external sunshade is that the installation space is small, its direction can be adjusted at any time according to the sun angle, and the energy-saving effect is obvious. However, affected by the shutter density, the viewing effect is poor. The vertical ecosystem belongs to a spatial three-dimensional sunshade. The distance between plants and glass is generally between 0.6 m and 3 m. The plants in a vertical ecosystem can be efficient about one year after being planted. The vertical ecosystem is not as good as

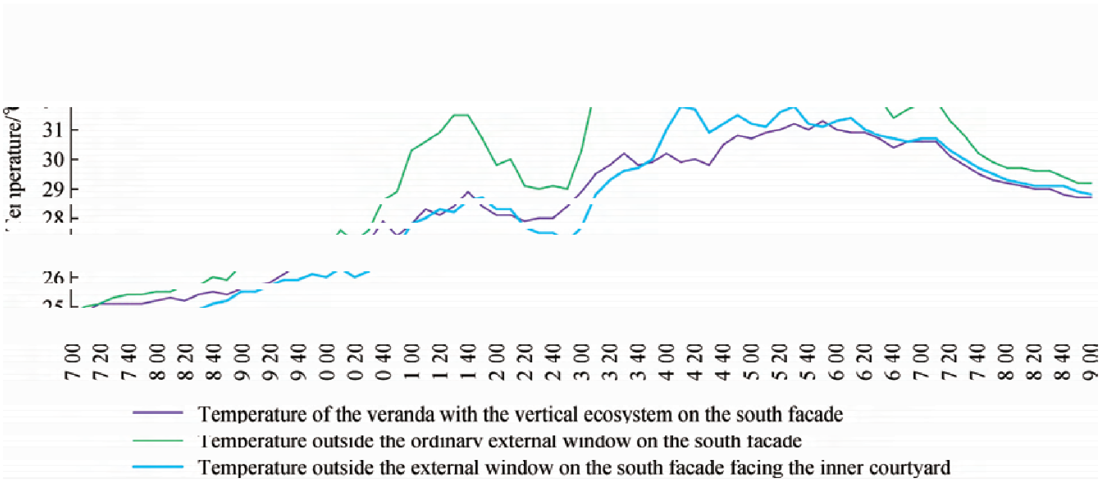


Fig. 24 Temperature on the south facade (during a typical day)

the electric external sun-shading roller shutter, which can achieve a comprehensive sun-shading effect. However, the plants have good ornamental efficiency, good visual experience, and no power consumption, and the plants change more vividly with the season change. In particular, in office buildings, vertical ecosystems can effectively alleviate visual fatigue and relax the users' bodies and minds.

Based on the measurement data, the temperature of the veranda with the vertical ecosystem, the surface temperature of the electric external sunshade blinds, and the ordinary external window surface temperature on the west building facade were selected for the comparative analysis. According to the analysis results (see Figs. 25 and 26), the temperature of the veranda with the vertical ecosystem is significantly lower than that of the ordinary windows in the afternoon due to the heat of the setting sun. For example, the average temperature difference between 12 noon and 5 p. m. on the second day reached 3.4 ℃ (see Fig. 26), whereas the temperature change in the rest of the day is not very obvious. As the electric external sunshade blinds use metal blades, their surface temperature is about two points higher than the outdoor temperature in the afternoon. However, due to its obvious overall sunshade effect, it is still highly efficient for indoor energy conservation.

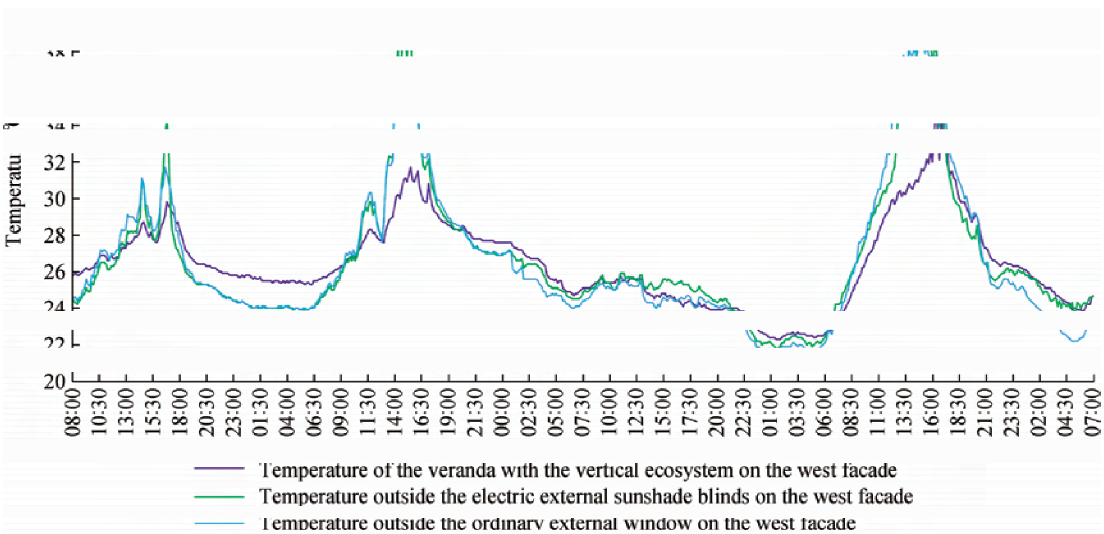


Fig. 25 Temperature on the west facade (4 consecutive days)

3.4 Summary

Based on the comparison results of the external surface temperature data of different building facade types on the east, west, and south facades, when the outdoor temperature is above 27 ℃, the vertical ecosystem has obvious advantages in energy conservation, especially on the west side. When the temperature is lower than 25 ℃, it hardly has an energy-saving advantage among the different kinds of building envelope types. If the double-glazed curtain wall system cannot achieve enough ventilation, it will cause a temperature increase in channel between twoglass layers under the solar heat, which will result in an increase in the building energy consumption.

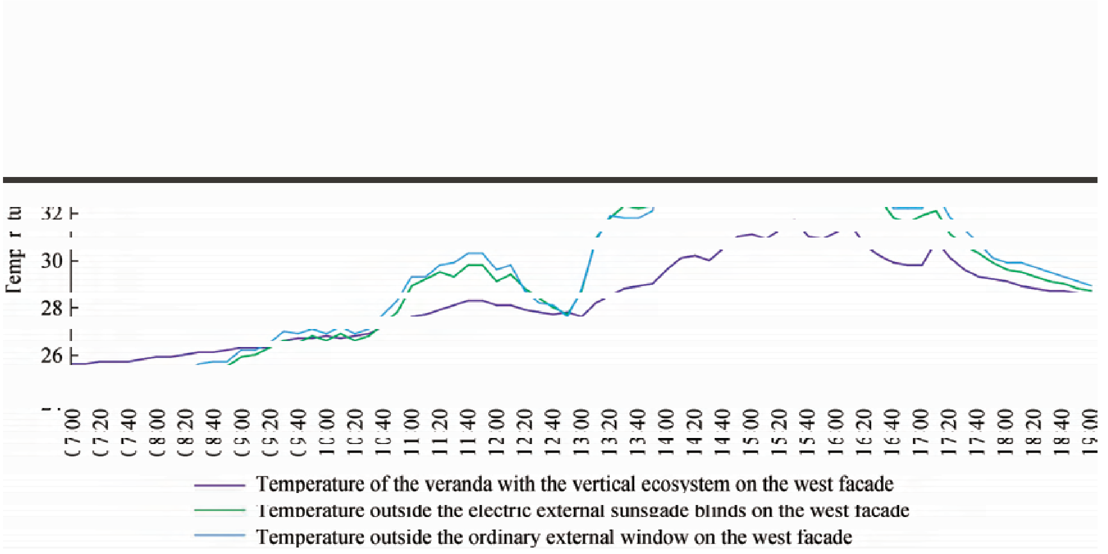


Fig. 26 Temperature on the west facade (during a typical day)

4 Post-occupancy Evaluation

To verify the actual effect of the vertical ecosystem set in the range of architectural boundaries in actual use, a post-occupancy evaluation questionnaire was distributed to the users, which is mainly aimed at the office staff using the project.

With the help of the Tencent questionnaire tool, 347 questionnaires were collected. 95.9% of the respondents were between 25 and 35 years old, of whom 66.9% were male. According to the questionnaire collected, 69.6% of the staff goes to the veranda more than twice a day. From the perspective of the use function, 59.6% of the staff answer and make calls on the veranda, 33% choose to rest and relax on the veranda, 22.6% of the female users choose to detour through the veranda to other offices, whereas only 9.5% of the male users choose the same option. From the perspective of stimulating employees' innovation, 42.8% of the staff believes that a beautiful outdoor green environment is more conducive to stimulating employees' innovation and creativity than a quiet indoor office environment. Meanwhile, 58.2% of the staff chooses to reduce the area of working tables, while the total area remains unchanged, to add a semi-outdoor area for oxygen absorption and communication.

To sum up the above information, the veranda with a vertical ecosystem not only has a better energy-saving effect but also brings higher value during use in terms of the users' feedback, relaxing the body and mind, promoting staff communication, and stimulating staff innovation.

5 Conclusions

1) The Tus-Design headquarters office building belongs to the transformation project of "Retreat into Three" in the urban renewal of Suzhou Industrial Park[15]. In addition to functional adjustment, the project transformation hopes to further improve the green design. At the beginning of the design, the architects focused on the convenience of later operation and maintenance of green buildings. The design hopes to provide a green building with self-growth ability while saving energy. The architectural design ensures sufficient natural lighting and ventilation environment through a reasonable architectural layout and provides a space and platform for the natural growth of plants.

2) Through 10 years of follow-up and comparative analysis after completion, the comparison and analysis of the plant's growth and change in the vertical ecosystem of the Tus-Design headquarters office building in four different aspects, i. e., the growth and performance of different plants on the same side of the building, growth and performance of the same kind of plants on different sides of the building, plants' growth in four seasons, and biodiversity change after the renovation, show that the ecosystem in the renovation project has significant effects on energy-saving and maintaining biodiversity.

3) The energy-saving effect of the vertical ecosystem is becoming better with the growth of the plants. From the actual data, compared with the ordinary windows, double-glazed curtain walls, and sunshade blinds, the vertical ecosystem has the most obvious advantage in energy-saving when the outdoor temperature is over 27 ℃, especially on the west building facade. At the same time, it provides users with a semi-outdoor rest space without energy use so that people can continue to enjoy the vitality of nature and enjoy the changes in seasons throughout the year. Furthermore, when buildings and nature achieve symbiosis, they will not get old through the years but will glow with more vitality.

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建筑边界区域立体绿化节能技术的实证研究

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摘要:根据启迪集团办公楼项目连续 10 年的观测数据,研究和分析建筑边界区域上生态节能技术的实际应用效果. 首先,研究建筑 4 个朝向的立体绿化植物特性、各种植物在不同朝向 10 年生长情况的对比及植物在一年中 12 个月的变化对比,总结出植物选择搭配应与建筑朝向、植物特性相结合,落叶与常绿植物搭配使用才能达到较好的遮阳节能效果. 然后,对垂直生态系统、双层玻璃幕墙系统和普通玻璃幕墙系统的节能温度进行数据实测,结合数据分析得出垂直生态系统在实际使用中可以达到更好的节能效果. 研究结果显示:当室外温度在约 27 ℃以上时,立体绿化系统具有较为明显的优势,尤其在西侧优势更为明显;低于 25 ℃ 左右时,其节能优势较小.

关键词:绿色建筑;绿色生态节能技术;立体绿化;遮阳;建筑改造

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