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Development of Biophilic Design in Primary and Secondary School for Health Promotion

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ABSTRACT: Biophilic design is an important approach for health intervention in the use of nature force, aiming to provide an environmental strategic plan for health promotion based on existing scientific evidence. This paper provides a systematic research of biophilic design in primary and secondary school embraces both practices and scientific research. Biophilic design evolved from perceptual practical exploration to scientific research, and from a direct natural model of physical health to a systemization design of overall health. This paper summarizes the relationship between the space environment and health benefits through an interdisciplinary literature research. According to the existing basic model of biophilic design, this paper puts forward the key points of primary and secondary school buildings from three aspects, direct experience of nature, indirect experience of nature and abstract perception of nature.

KEY WORDS: health promotion; biophilic design; primary and secondary school; spatial environment; health benefits

Introduction

Artificial, indoor, and static lifestyles have led to the prevalence of "nature deficit disorder"(NDD)[1] among children and adolescents and opened the door to the associated health risks. Although the concept of nature as a health resource has been around for a long time, how does nature play a health-promoting role for the special population of children and adolescents in the specific space of primary and secondary school buildings? How can primary and secondary school buildings tap into the power of nature in their design?

Preventive medicine points out that the most efficient and and cost-effective method of intervention is to target the specific environments of different age groups [1-2], and hence the scientific regulation of health risks for children and adolescents through spatial configuration in the built environment of primary and secondary schools has enormous benefits for the health of the entire macro-population. Figure 1 shows the position of the spatial environment of primary and secondary schools in life course interventions. The current health situation of children and adolescents in China does not inspire optimism, and the occurrence and development of many health problems are related to the environment to some extent [3]. Common approaches to health promotion include environmental, dietary, medicative and managemental ones [1], but what is more popular than letting children enjoy nature? Primary and secondary schools are the environment where children and adolescents spend the longest amount of time consciously, and it is urgent to revisit the current primary and

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secondary school environment from a health perspective. In this paper, relevant scientific research and practical applications are reviewed to provide a reference for the design and improvement of basic education facilities.

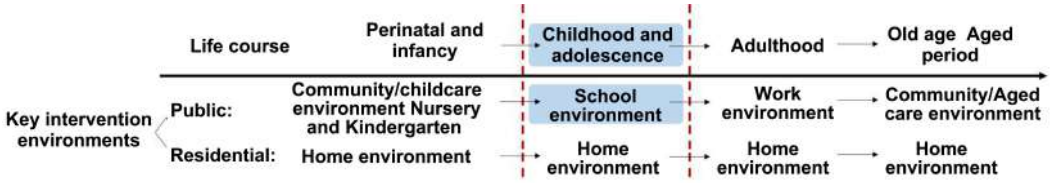

Figure 1 Schematic representation of environmental strategies for health interventions across the life course

1 Origin of biophilic design for health promotion

The term "biophilic" was coined by Professor Edward Wilson, a member of the National Academy of Sciences, in his 1984 book *Biophlia* [4], which originally meant the love of life and the nature of humans to be close to the natural elements that are beneficial to their survival, reproduction and prosperity. "Biophilic design" is not simply a return to nature in the primitive sense but focuses on how to satisfy people's inherent wish to be close to nature in artificial environments, turning to natural elements and laws as solutions to the complex problems faced by human beings. It is a reexamination of the relationship between natural and artificial forces, and the more highly artificial the environment, the more in-depth biophilic design of the environment is needed. Stephen R. Kellert, an expert in biophilic design, categorizes biophilic design into three modes: direct experience of nature (direct introduction of natural elements), indirect experience of nature (association with nature), and abstract experience of nature (creation of natural spatial sensations) [5]. Although the concept of biophilic design was introduced later, the idea of pro-nature and its exploration in design appeared much earlier. Another concept that is very similar to biophilic design is "nature-based solution," which played on the polysemy in the word "nature," as the solution itself is indeed a design based on human nature [6-7]. Compared with "nature-based solution," "biophilic design" pays more attention to stimulating the user's intrinsic characters through design, emphasizes the coupling of the role of nature and the user's agency, and is more in line with the study of specific spaces for specific groups of people. Therefore, this paper adopts the expression "biophilic design."

In the 1980s and 1990s, "health promoting," "active living by design," "evidence-based design" and other related concepts were successively proposed. Despite the differences in their positions and perspectives, many of the research results show interoperability with, support for, and promotion of biophilic design. The term "health promoting" was proposed by the World Health Organization (WHO) in the Ottawa Charter in 1986 [8], with the aim of enabling people to do everything possible to keep themselves in the optimal state of mind and body by making healthy choices, and its definition of health covers the physical and mental dimensions as well as that of social adaptation. The "health-disease continuum theory" states that the human body is in a state between healthy and clinical states [1], and that health promotion is to orient the body toward the healthy pole as much as possible through a variety of means, including the natural environment (Figure 2). "Active living by design," also developed in the United States [9], highlights the use of multilevel and multidisciplinary approaches to improve people's physical activity, with a particular emphasis on the impact of the environment on daily life. "Evidence-based design" emphasizes design based on rigorous scientific evidence and relies on practice to validate the relationship between the environment and people. Biophilic design for health has gradually taken shape on three levels: practice, theory and research, and has inspired many researchers and creators in a variety of fields, including healthcare, office, housing and education. For example, in an essay published in *Science* in 1984, Professor Roger Ulrich' points out that outdoor green landscapes may affect the recovery of surgical patients [10], and this landmark study advanced the concept of biophilic environment for health to the height of scientific research, and then a large number of scholars followed suite, studying the link between nature

and human behavior, psychology, disease and other aspects. Therefore, "biophilic design for health" is a comprehensive concept involving multidisciplinary contexts based on relevant theoretical and empirical studies.

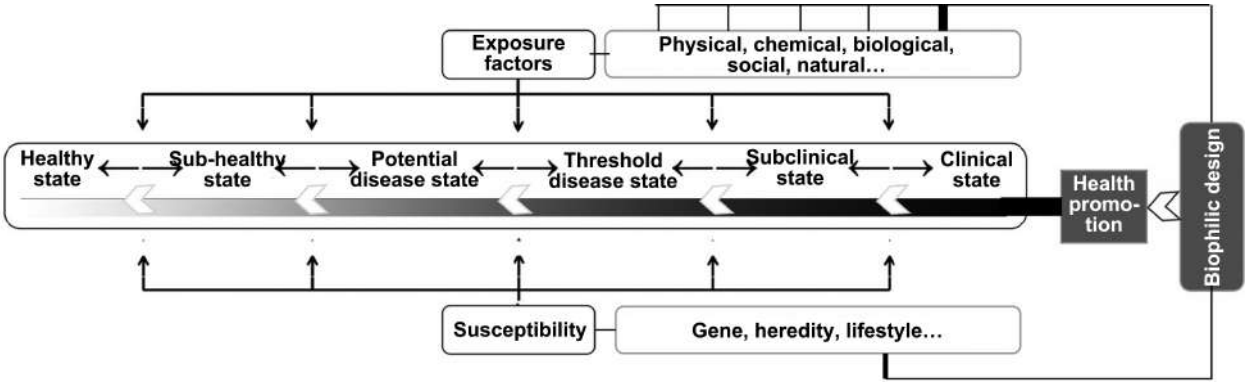

Figure 2 Illustration of the relationship between health promotion and the "health-disease continuum theory"

2 The development of biophilic design for health promotion in primary and secondary school buildings

The influence of biophilic design on children's and adolescents' health has always existed at the objective level, but due to the influence of such factors as social background, educational philosophy, public health, and scientific research means on the process of recognizing the relationship between the two, the relevant practical explorations and scientific research don't completely coincide with each other at temporal and geographical levels. Taking the social event of rethinking the education environment in response to a specific health problem at the beginning of the 20th century as the starting point, this paper reviews the development of biophilic design in primary and secondary school architecture, which can basically be summarized into five stages.

2.1 Germination: a pioneering movement that began with specific physiological health needs

During the Enlightenment and the Industrial Revolution, when the scope of education expanded and the number of educated people increased, primary and secondary school buildings emerged for efficient education and effective management [11]. The health performance of primary and secondary school buildings has always been of great concern due to the high-density of crowds inhabiting them and the high social concern for children and adolescents. The integration of architecture with the fields of medicine and public health was first shown in the prevention and control of infectious diseases [12], and the same is true for primary and secondary school buildings. A prominent example of primary and secondary school design specifically targeting health issues was the "open-air school movement" [2] in 1904 in the community of Charlottenburg, Germany, which aimed to allow frail children (especially children with tuberculosis) to receive a normal education. Focusing on adequate sunlight and fresh air, the two most essential elements of the life support system, and advocating that educational activities be conducted in open spaces or outdoor environments, this movement of educational environments targeting special physiological health needs was subsequently expanded to other countries in Europe and the United States [13], and had a far-reaching impact on primary and secondary school architectural design, which can be regarded as the germ of biophilic design for health in primary and secondary school architecture.

2.2 Exploration: a direct nature experience model to serve universal health needs

Influenced by the open-air school movement, the practice of biophilic design in primary and secondary school buildings hasled to a variety of explorations of physical health, mental health, and their relationship with education, but the introduction of the natural environment is limited to the cognitive level of direct experience. In the 1920s to 1950s, it was believed that healthy children should enjoy similar pro-nature education, and health-related elements such as sunlight, air, physical exercise, safety and hygiene should be reflected in school buildings.

The most typical example is Jan Duiker's four-story Open Air School in Amsterdam, the Netherlands, designed specifically for normal children in 1928 [13-14], which enhances the integration of architecture and nature through transparent common classrooms, shared open classrooms, and overhanging structures (Figures 3-5). During this period, educator Maria Montessori proposed interactive schools, arguing that children observe and learn from the natural environment based on their nature, that the school environment not only affects physical health but also shapes children's mental health, and that proximity to nature and the outdoors is essential to the school environment. Following this, Richard Neutra emphasized that school design should be based on the reality of human physical and mental health, and more directly proposed natural school design [13], which was related to the experience he accrued working in the organic architect Frank Lloyd Wright's Taliesin and designing a health villa for Dr. Rowell, and he referred to his design as "Bio-realism" [15] represented by the Corona Avenue School and the Skeet Road Elementary School (Figure 6), with design elements such as large transparent sliding walls and semi-outdoor activity areas fully expressing the architectural characteristics of the Bio-realism school, where assemblies, meals, and classroom activities can take place outdoors. The influence of natural schools is far-reaching and can still be seen in academic discussions and design practices of green and healthy campuses today.

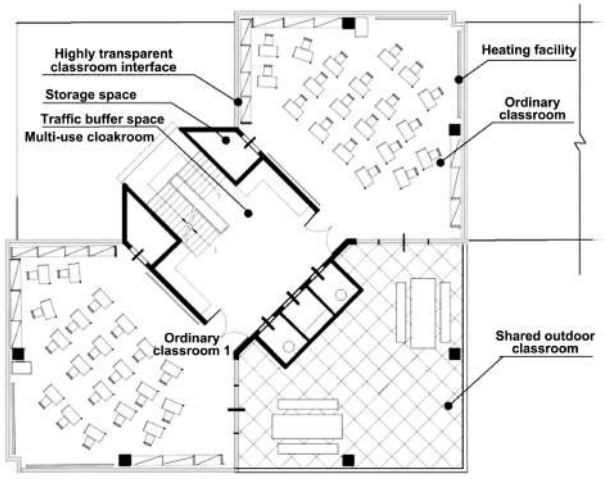

Figure 3 Classroom units of Amsterdam Open Air School

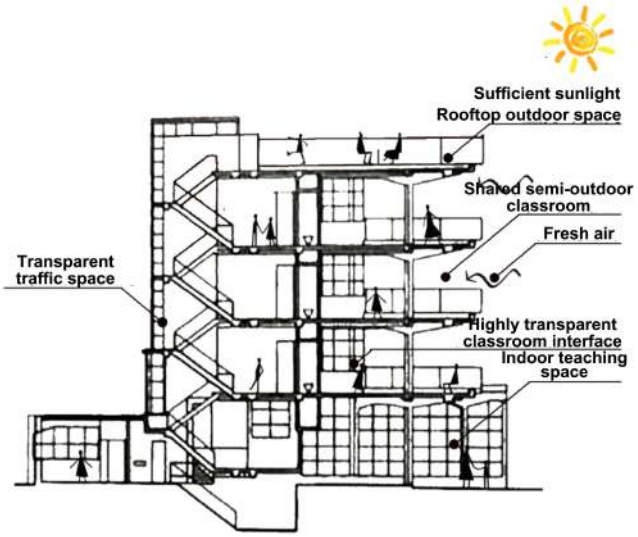

Figure 4 Sectional analysis of Amsterdam Open Air School

Figure 5 External view of Amsterdam Open Air School

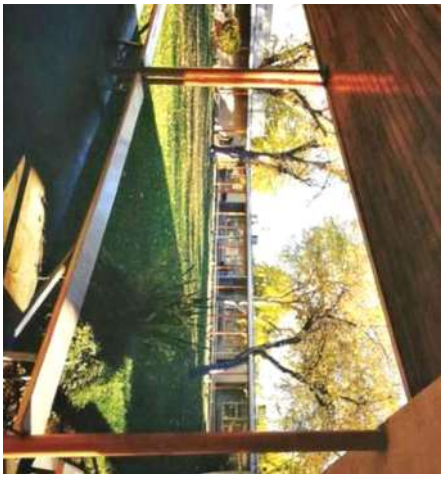

Figure 6 External view of Skeet Road Elementary School

2.3 Stagnation: a period of retrogression in pro-biotic design constrained by social contexts

After the 1950s, the economies of various countries

began to recover after the war, and basic education assumed the role of efficiently improving the quality of the workforce. Influenced by standardized process management in assembly lines, the "class-based teaching + standardized classroom" model prevailed [16], resulting in a typical corridor series multi-story building design, meeting only the basic physical health need while considerations for mental health and social adaptation considerations were extremely lacking. This nearly uniform paradigm of primary and secondary school building space model was widely used in the world, and although it has been criticized by educationalists, it still has a wide influence until today.

The development of China's primary and secondary school architecture mainly took place after the founding of New China, and the *Architectural Journal*, as the earliest architectural periodical in China, has published a total of 56 domestic primary and secondary school design cases since its inception in 1954, which formed the epitome of China's primary and secondary school architectural design exploration. From the 1950s to the 1980s, "running schools frugally" was the main guiding ideology, and the basic functions of school buildings were stretched to the limit, as represented by the newly built Hongguan Middle School and Hedley Primary School in Shanghai in 1962 [17], which were characterized by a centralized layout of the inner corridor, with a relatively closed space, let alone the construction of the public activity space, campus greening and landscape, and the biophilic design of primary and middle school buildings almost bottomed out. It was not until the 1980s that architects gradually began to explore landscape design for the campus, as seen in the design of Nanjing's Langya Road Primary School in 1986 [18].

2.4 Development: multiple nature experience models for overall health

With the development of society, people's awareness of campus health sees an increase, and at the same time, life education, nature education, quality education and a series of concepts impact on the traditional education model, all of which require changes to campus architecture. In 1977, the United States professor Gorge L. Engel put forward to the "bio-psycho-social" medical model as a substitute for the biomedical model [19], marking a new period of overall health in the consideration of health. The response to the overall health concept in the field of architectural design of primary and secondary schools in China began with the 1986 edition of the "Architectural Design Code for Primary and Secondary Schools." Since then, health standards such as lighting, ventilation, safety, greening, and indoor facilities in primary and secondary school buildings have been significantly improved. After entering the 21st century, in addition to "safety," "applicability," and economy," keywords such as "health," "green," "ecology," "venue," "atmosphere," "fun," "life," "experience" and "adaptation" emerged in various architectural journals and were used to describe newly published primary and secondary school cases. The architectural design practice of primary and secondary schools gradually broke through the stereotyped model of corridors in series, looking for more friendly and diverse spatial models, providing students with opportunities to perceive nature through the openness and transparency of space. "Learning etiquette under the big tree and teaching beside the apricot forest" once described a teaching model with direct nature as the background. However, as built environment becomes the absolute mainstream learning place, the biophilic design of primary and secondary school buildings must be systematically conducted from spatial mode to indoor environment. Based on the medical model, biophilic design has developed into a multiple natural experience design for overall health at the practical level.

First, direct experience of nature is used as the basic strategy of biophilic design. By mobilizing the visual, auditory, tactile and other sensory systems, the direct stimulation of nature is brought into play, and the interactive relationship between architectural space and nature is emphasized. For example, Suzhou Science and Technology City Experimental Primary School proposed the concept of vertical academy, breaking the integrity of the building interface to form a staggered outdoor platform, and adopting

internal courtyards and three-dimensional gardens (Figures 7-8) [20]. Figure 9 shows a summary of the key points of direct experience of nature design for a large number of primary and secondary school buildings. Secondly, indirect experience of nature is used as an auxiliary strategy of biophilic design. By extracting natural elements, natural materials and natural features, beautiful associations about nature are stimulated, thereby exerting psychological comfort [5]. Children and adolescents have keen imaginations, and indirect experience of nature is based on this active expansion of natural feelings. For example, in the design of Hongling Experimental School, O-Office extracted the context of "mountain" and translated the intention of "valley," combining them with three-dimensional greening to form a feeling of being in a valley (Figures 10-11), realizing the mutual communication between artificial environment and natural intention, and making a particularly valuable contribution to the exploration of biophilic design in high-intensity development. Another example is that in the bathroom design of Munkegaard School in Denmark, where the natural patterns integrated into the wall and floor completely activate this space closely related to public health (Figure 12), reversing the tendency to ignore the bathroom as an auxiliary facility. Thirdly, using abstract experience of nature as an enhancement strategy for biophilic design, creating a built environment that allows for abstract perception of the laws of nature through spatial patterns is closely related to health issues such as learning pressure and social adaptation for children and adolescents, and is the most arcane and covert connotation of architectural biophilic design. For example, the teaching unit design of Hangzhou Future Science and Technology City Primary School, on the basis of supporting a one-to-many teaching model, forms a relatively private auxiliary space, and enhances students' social behavior around the computer information center, exploring a classroom unit that is more conducive to children and adolescents' emotional cognition, social adaptation, and autonomous learning (Figure 13).

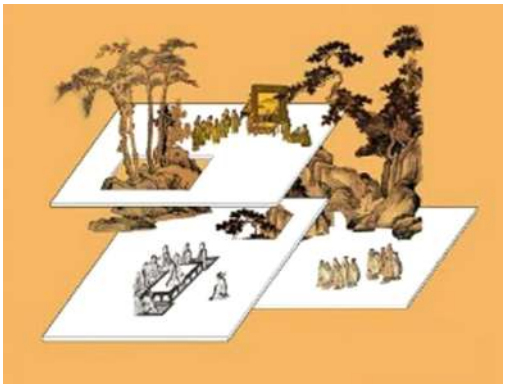

Figure 7 Concept and translation of vertical academy

Figure 8 Experimental Primary School of Suzhou Science and Technology Town

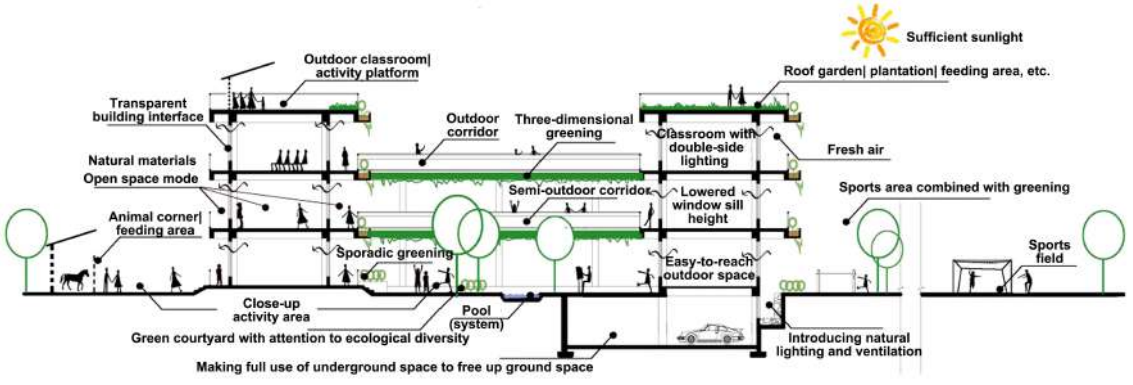

Figure 9 Key points forintegrating direct experience of nature in design of primary and secondary school buildings

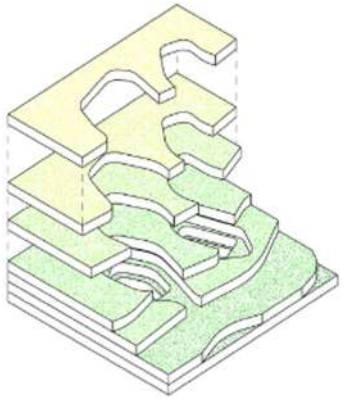

Figure 10 The context and translation of "valley"

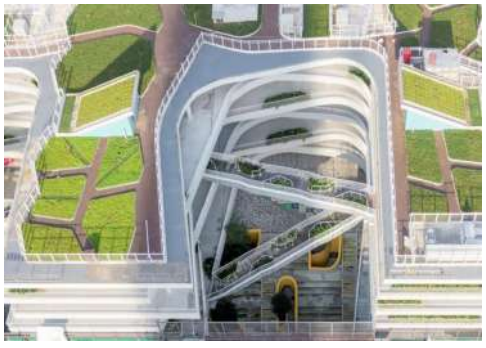

Figure 11 Hongling Experimental Primary School

Figure 12 Public space for indirect experience of nature

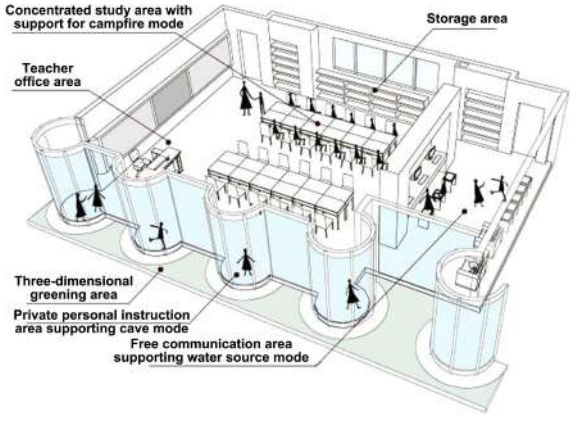

Figure 13 Teaching unitfeaturing abstract experience of nature

2.5 Deepening: relying on the continuous advancement of scientific research

The relationship between natural forces and health in design practice ultimately remains in discussions at the conceptual level. After entering the 21st century, with the development of multi- and cross-disciplinary research, the accumulation of relevant results, and the promotion of evidence-based design, the biophilic design of school buildings has entered a scientific advancement period. On the one hand, the biophilic design methods reflected in practical exploration deserve more rigorous verification. On the other hand, the relevant results in the field of scientific research need to be implemented through the promotion of design codes and concepts.

Multidisciplinary research points out that health is the result of the complex interaction between genetic susceptibility and environmental exposure. Extracting the relationship between "biophilic design-health benefits" for children and adolescents from the complex research is conducive to further deepening biophilic design. The focus of research in this field is affected by factors such as the typicality of children and adolescents' health problems and their relevance to biophilic design. First of all, the research on physiological health is the most basic, among which the related research on visual health, respiratory health, physical activity, etc. is relatively high in quantity and awareness, and to this day, these three types of problems are still typical health problems faced by children and adolescents in our country. Secondly, the disease phenomena of emotional tension, psychological anxiety, school rebellion, depression, etc. among children and adolescents are aggravating. In return, the attention paid to the mental health of children and adolescents has also increased generally. Thirdly, social adaptation, as the third connotation of health, refers to the self-regulation of human beings to their environment, including the adaptation status to school and the adaptability to the future. The campus plays a transitional role between family and society. Problems such as interpersonal relationship barriers and school bullying reflect that the current social adaptation and moral health of children and adolescents do not allow for optimism. This study clarified the specific relationship

between promoting the health of children and adolescents through biophilic design through interdisciplinary literature research, as shown in Table 1. The results of the correlation study on "biophilic design-health benefits" of primary and secondary school buildings revealed the basic characteristics of biophilic design for health promoting: (1) natural elements do not have the same health benefits; (2) there are targeted characteristics between specific natural elements and specific health problems; (3) the health benefits of biophilic design elements have systematic superposition characteristics; (4) Introducing nature into design without caution may bring corresponding health risks. On this basis, the elements of campus biophilic design are refined, and Table 2 further clarifies the systematic correlation between direct experience of nature, indirect experience of nature, abstract experience of nature and the health of children and adolescents. In summary, we believe that the biophilic design of primary and secondary school buildings based on scientific research results is in a stage of continuous deepening.

Table 1 Evidence in research on "biophilic design-health benefits" of primary and secondary school buildings

Health problems	Representative research conclusions related to biophilic design	Closely related disciplines
Visual health [21-23]	• An environment with insufficient natural light can easily cause visual fatigue; • Natural strong light has the effect of preventing myopia, which is manifested in biological effects such as promoting the secretion of retinal dopamine; • The most direct way to obtain natural strong light is to extend the outdoor exposure time; • Research on the prevention of myopia through outdoor exposure has overturned the traditional concept of preventing myopia through exercise; • A more open spatial model promotes children's outdoor exposure; • The recovery time of children's visual fatigue is about less than 10 minutes, and green plants can help relieve visual fatigue.	Ophthalmology Preventive medicine
Respiratory health [24-26]	• It covers a variety of diseases such as acute and chronic diseases, and is affected by multiple environmental factors such as physical, chemical, and microbial ones; • The respiratory health of children and adolescents is closely related to campus microclimate and classroom air quality; • Green plants are beneficial for campus microclimate regulation and air purification; • Health problems such as rhinitis and allergies are related to air quality, pollen, flying catkins, mold index, etc..	Microbiology Hygiene Clinical medicine
Physical health [10, 23, 27-30]	• Insufficient physical activity threatens the health of children and adolescents. The environment can affect physical activity through multiple pathways, including behavioral, psychological, and physiological ones. Active design can promote physical activity. • Optimizing the location, layout, visibility, accessibility and vegetation density of campus activity venues can help increase the amount of activity. For example, the green area mixed with artificial facilities is the most frequently used and attractive activity area; measures such as providing activity space during breaks, configuring a weatherproof playground with good natural lighting, increasing the proportion of semi-indoor and semi-outdoor spaces, and providing a variety of outdoor activity spaces can all increase the amount of activity.	Behavioral science Preventive medicine Sports science
Mental health [31-33]	• The environment can be both a source of psychological stress and a way to relieve it; • The environment can affect mental state through behavior, perception, memory, imagination, thinking, language, emotion, etc.; • Urban primary and secondary schools lack natural resources in general and have a serious lack of restorative environments; • Green environment, landscape items, and psychological adjustment space can relieve psychological pressure to a certain extent; • The natural environment has better stress relief and fatigue recovery effects than the artificial environment; • The restorative benefits of the environment are most effective through direct visual stimulation of natural elements. Ranked second is the psychological association promoted by indirect elements. The abstract spatial pattern is more of an activity support and stress prevention, and its short-term restorative effect is not significant.	Psychology Education

(Continued)

Health problems	Representative research conclusions related to biophilic design	Closely related disciplines
Social adaptation and moral health [16, 33, 34、35]	• Campus buildings should provide a campus environment that is consistent with the nature and age characteristics of children and adolescents and is conducive to promoting emotional regulation, social cognition, and active life; • A biophilic environment can better support children's health, communication, and the diversity of games and the friendly campus space model promotes children's communication; • Children with ADHD are more likely to concentrate after contact with nature; • A campus environment rich in greenery has a positive impact on the development of children's autonomy and collaboration; • A biophilic campus design improves learning efficiency; • Playing in a variety of natural environments can reduce school bullying.	Sociology Education Psychology

Table 2 Correlation matrix between biophilic design elements and health issues

Biophilic design elements		Visual health	Respiratory health	Physical activity	Psychological health	Social adaptation
Direct nature	Natural light	★	—	○	★	★
	Air	—	★	○	—	—
	Water	—	○	○	▲	○
	Vegetation	★	★	★	★	★
	View	○	—	—	▲	▲
	Natural materials	—	○	—	▲	▲
Indirect nature	Concrete features	—	—	—	▲	○
	Abstract features	—	—	—	▲	○
	Simulation of dynamic changes in nature	○	○	○	○	○
Abstract nature	Spatial mode	★	★	★	▲	▲
	Spatial feel	—	—	▲	▲	▲
	Distance	○	—	○	—	○

Notes: ★ Empirical research evidence; ▲ Theoretical research and applied research; ○ Logical reasoning based on similar research in other environments; — No specific research has been found yet.

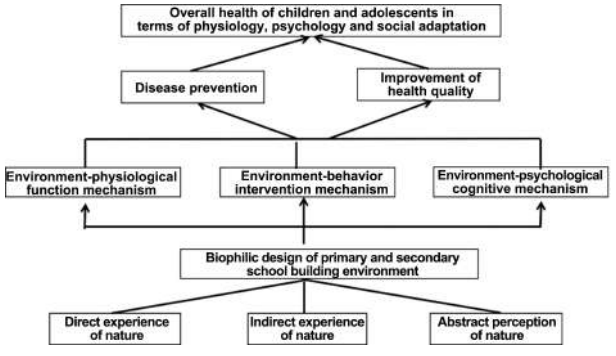

Figure 14 Schematic diagram of the mechanism of biophilic design in health promotion

3 Conclusion

The core of biophilic design is to stimulate the inner nature of children and adolescents, give play to the positive effects of nature at the physiological and psychological levels as well as social adaptation, and provide a supportive environment for promoting health as much as possible, which are also the basic responsibilities of the design and research related to primary and secondary school buildings. Through a systematic review of the practical exploration and scientific research of biophilic design in primary and secondary schools over the past century, the following conclusions can be drawn, First, there is a direct correlation between the health problems of children and adolescents and the environment, and the impact on the health of children and adolescents is mainly manifested in prevention and health promotion, with additional manifestations in healing. Second, all kinds of natural elements do not have the same health benefits, and cross-verification of related multidisciplinary results is more likely to offer systematic guidance. Third, the "biophilic design-health benefits" relationship can be preliminarily summarized as

the environment-physiological function mechanism, the environment-psychological cognitive mechanism, and the environment-behavior intervention mechanism. The three are combined to jointly play a role in disease prevention and health quality improvement (Figure 14). Fourth, the research scope of environmental biophilia has expanded from direct natural elements to the biophilia of the overall spatial environment. The design of primary and secondary school buildings should form a systematic design concept based on the direct experience of nature as the basic strategy, the indirect experience of nature as the auxiliary strategy, and the abstract experience of nature as the enhancement strategy.

Our country is in a period of development of new construction, expansion, and reconstruction of basic education facilities. The health situation and education reform jointly call for the biophilia of campuses. The biophilic design of primary and secondary school buildings takes the inherent nature of children and adolescents as the starting point and re-examines the relationship between educational environment and natural experience from the perspective of health promotion. In the past ten years, studies on the impact of the natural environment on human health have developed towards quantitative research, including environmental factors, natural doses, physiological feedback, behavioral records, psychological reactions, etc., which can be studied more deeply through human factors feedback technology, mobile monitoring technology, virtual reality technology, big data, etc. The simultaneous analysis of multimodal data is expected to further reveal the deep impact of biophilic design on the health of children and adolescents [36]. Whether it is a school located amidst mountains and rivers or a school in a high-density urban area, there are opportunities for improvement from spatial patterns to natural elements. The more artificial the environment, the more it can reflect the health benefits of biophilic design. The design and operation of primary and secondary school buildings should take biophilic design as a strategically valuable approach throughout.

Figure and table sources

Figures 1, 2, 9, 13, and 14 are drawn by the author; Tables 1 and 2 are drawn by the author; Figures 3-4 are redrawn; Figures 5-6 are quoted from Hiller. Modern School Design: A Century Long View of Educational Architecture Design [M]. Electronic Industry Press, 2014

Figures 7-8 are quoted from Zhang Bin, Li Shuo. Vertical Academy - Design Notes of Suzhou Science and Technology City Experimental Primary School [J]. Journal of Architecture 2017 (6): 67-69.

Figures 10-11 https: // www. gooood. cn/hongling-experimental-primary-school-china-by-o-office-architects.htm

Figure 12 Duan Qian (ed.), World Architecture Series: School Architecture 1 [M], Liaoning Science and Technology Press, 2015.

Notes

1) Nature-deficit disorder: Originally proposed by Richard Louv in *The Last Child in the Woods*, it refers to a common social phenomenon in which children spend less and less time in nature, and the highly artificial environment erodes the lives of the new generation, thus bringing about many behavioral and psychological problems.

2) Open-air school movement: InRepublic of China, the activity of teaching poor children outdoors due to the shortage of educational resources was also named "open-air school movement," but this is essentially different from the open-air school movement in Europe and the United States mentioned in the article, the intention of which was to gain fresh air and sunshine.

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Quality and Accessibility of Urban Parks from a Child-Friendly Perspective: A Case Study of Preschool Children in Barcelona

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ABSTRACT: Access to green spaces and playgrounds is a core indicator in the measurement of child-friendly cities and one of the necessary services provided by urban parks. This article focuses on preschool children with high demand and utilization rates in urban parks, and attempts to construct a rapid analysis and evaluation method that comprehensively considers the quality and accessibility of urban parks. Taking Barcelona, Spain's child-friendly city as an example, this article established a comprehensive framework, including the optimization of the Quality Index of Parks for Youth (QUINPY), and accessibility model based on field research, open source maps, official statistics, etc. Combining the population density distribution of preschool children, specific improvement suggestions are proposed—based on different needs and pain points, selecting suitable innovative measures such as improving the urban traffic and walking environment, rationally increasing structural facilities, or encouraging time-sharing and three-dimensional expansion of the possibility of space use. Hope this article can provide references for the development and construction of child-friendly urban parks in China.

KEY WORDS: child-friendly; urban parks; quality evaluation; accessibility; Barcelona

Introduction

In 1996, the United Nations Children's Fund and UN-HABITAT launched the Child-Friendly City Initiative (CFCI). The construction of a child-friendly living environment has made great progress in both international academic and practical fields. Currently, 1,157 cities and regions have obtained CFCI certification, but no city in our country has yet received this honor. CFCI emphasizes that children's living environment in cities, towns or communities should be safe, clean and tidy, with green spaces they can enter to play, entertain themselves and make friends. Urban parks are an important part of the green space mentioned in CFCI. They provide greenery and play space for children. They are the main portal for them to experience nature, understand society, and develop interactive relationships [1], and are closely related to children's physical and mental health, social skills and personal development [2-5]. As one of the key points in constructing child-friendly cities, whether urban parks have the quality that meets children's needs and whether the public have convenient access to them are key issues at present, and they are among the hot topics in the discussion of landscape fairness [6-10].

In terms of child-friendliness, children of different a-

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ges have different needs for parks.Preschool children are an important and special type of "users" in parks. The needs and usage methods of this group are significantly different from others and are not easy to accurately understand, and they are often one of the main groups using parks. Therefore, this study focuses on preschool children and selects urban parks in Barcelona, Spain as a case to explore their quality and accessibility. On the one hand, Barcelona was awarded CFCI twice in 2007 and 2018, and has accumulated rich experience in the construction and management of child-friendly urban parks; on the other hand, Barcelona's climatic conditions are similar to those in some parts of our country, encouraging and suitable for children's outdoor activities, which is in line with the child-friendly construction goals of some cities in our country. In view of this, this study further attempts to construct an evaluation method that encompasses the internal quality and external accessibility of urban parks, so as to provide a reference for the child-friendliness oriented development and construction of urban parks in our country.

1 Concept definition

1.1 Urban park quality based on a child-friendly perspective

The services and benefits urban parks bring to children often vary with the quality of the park [11]. Urban park quality refers to the internal characteristics of the park including spatial design, maintenance management, safety, functional diversity, convenience facilities, etc. These factors can significantly affect the usage and benefits of a park [12]. The basic principle of quality evaluation is to effectively identify the people targeted by the park and evaluate whether the park most appropriately serves the groups that need the park most, especially relatively vulnerable groups such as low-income people, the elderly, and children [13]. Children are a group that is easily overlooked and underserved in park planning, design and management decisions [3, 14]. Accordingly, this study selected preschool children in the age range of 0-6 years old as the object of investigation. First, field surveys and literature prove that the age of children who frequently use parks is usually within this range [15], and children's play facilities also take this age group into consideration. Second, in terms of usage patterns, children of this age group are generally led by caregivers, who often choose parks based on distance and convenience; school-age children have a wider range of activities and are more capable, and their choice of parks is greatly influenced by preferences and peers.

Since 2000, the quality of urban parks has received more and more attention [8]. Its evaluation methods include the Quality of Open Space Tool (POST), Post Occupancy Evaluation (POE), the comprehensive evaluation model combining big data of online text and small data of questionnaires and interviews, etc. However, these methods rarely distinguish different age groups for analysis. This study focuses on preschool children, so the Quality Index of Parks for Youth (QUINPY) is introduced. This index is based on a geographical information system and constructs a child-friendly evaluation index system, which has been effectively applied in cases in European and American countries [16-18]. As far as this study is concerned, QUINPY is superior to evaluation methods that do not distinguish between groups and use many subjective indicators [6, 13] in two aspects. First, it fully considers the particularity of children's needs for park use; second, when the number of research subjects is large, results can be obtained quickly without relying on massive questionnaires and interviews, and it has been proven to have high validity and strong operability [17, 18].

1.2 Accessibility of urban parks

In this study, the accessibility of urban parks refers to the opportunities and difficulty of people entering different urban parks, aiming to measure the external "opportunity potential" of urban parks. There are buffer zone analysis, network analysis, and topological analysis of urban road networks for evaluating the accessibility of urban parks as a unit in the public service supply chain [19, 20]. The third method often uses space syntax theory and models to quantitatively explain the spatial structure and organizational laws mathematically with the help of graph theory, and it measures the accessibility of parks by calculating indicators such as integration and selectivity [21]. In terms of the research object, Barcelona's road network has good walking conditions, and most urban parks are

open, with multiple entrances. The topological data of the road network around the park can more accurately reflect the accessibility of the park; from the perspective of operability, it is relatively easy to obtain the ESRI Shapefile open-source vector data for the road network of the case site, and the spatial accessibility can be quickly calculated through the operation of space syntax, and presented intuitively in the form of tabular data and visual maps. Therefore, the space syntax model is introduced to conduct a more refined analysis of the supply side from the perspective of spatial relations. The method adopts a line segment model that fits the actual situation of preschool children entering the park by walking. This model can better simulate the walking connectivity between preschool children and urban parks, and it can intuitively reflect the supply and demand relationship when combined with the population density of preschool children in the area where the park is located.

2 Research design

2.1 Child-friendlycity Barcelona

Barcelona is the second largest city in Spain, with an area of 101 km^2 and a population of 1.62 million. In 2019, the city council managed more than 583.6 hectares of urban parks (Figure 1). Children account for 16% of Barcelona's population. The city council attaches great importance to the construction of child-oriented urban parks and is committed to "promoting the development of a municipal public life participation system with children as the protagonists."

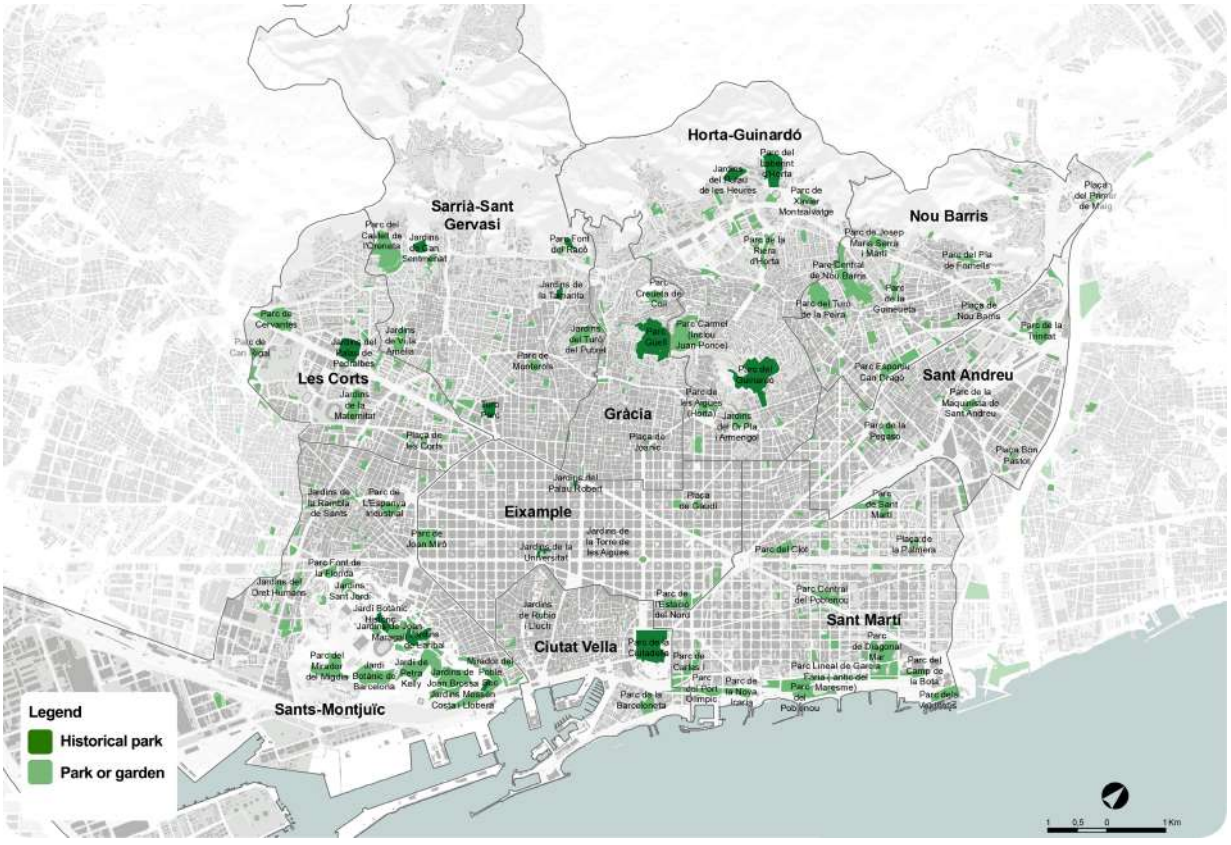

Figure 1 Distribution map of Barcelona's urban parks

2.2 Research methods and framework

Based on literature research and field research, we attempt to: (1) construct a child-friendly park quality evaluation system and conduct a corresponding evaluation of Barcelona's urban parks; (2) use the space syntax model to conduct an accessibility analysis of Barcelona's urban parks based on a line segment model; (3) integrate the results of quality and accessibility evaluations to conduct an superimposed matrix analysis and superimposed evaluation of urban parks; (4) supersimpose the population density of preschool children in each community for analysis, and explore the advantages and disadvantages of different

types of urban parks based on the evaluation results and put forward suggestions (Figure 2).

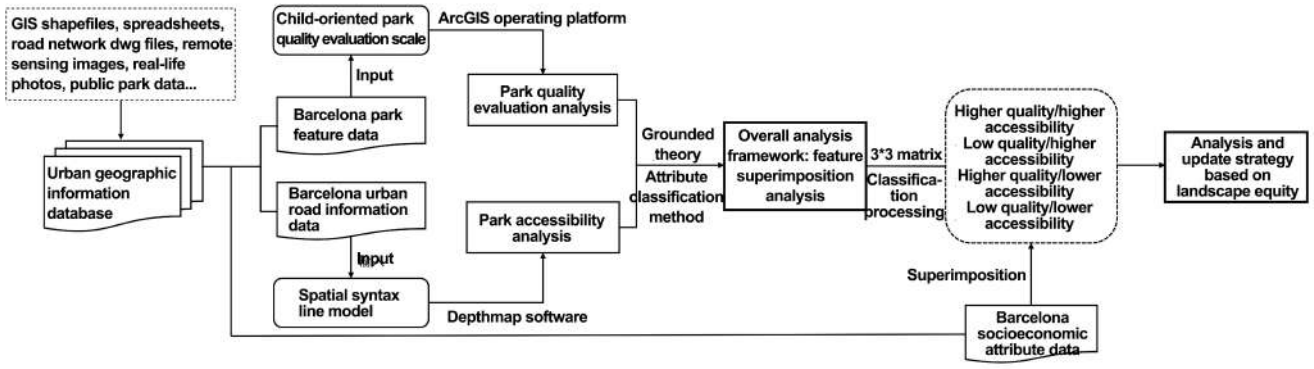

Figure 2 Research framework

Regarding the evaluation of child-friendly park quality, this study draws on the QUINPY proposed by Rigolon in 2016. The evaluation scale has a two-level structure and is constructed based on the following. First, databases such as Web of Science, Science Direct, Jstor and EBSCO host were searched, and "children" and "outdoor activities/parks/playgrounds/green spaces/public open spaces" were selected as keywords. A total of 80 closely related English literature in the fields of public health, landscape architecture, urban design, planning, environmental psychology and geography from 2000 to 2015 were screened. Based on this, the elements included in "park characteristics that attract children to play" and "green space characteristics preferred by children" were extracted and used as secondary indicators, because both characteristics have been widely proven to directly promote effective park use [11]. The secondary indicators obtained were then coded, and the indicators were regrouped and integrated using grounded theory, summarized into five categories of primary indicators, and the indicator counts appearing in the literature were used as the basis for weighting. The above study also further verified the effectiveness of the evaluation scale. It selected Denver, USA as a case city and invited well-known experts in the field to evaluate and rank the quality of the city's six parks, proving that the evaluation results of the scale are effective [16].

Based on this scale, the present study made the following adjustments based on the current characteristics of Barcelona's urban parks, the current child-friendly policies, interviews with local relevant departments such as the Urban Parks Institute and the Children and Youth Institute, and field interviews with park users. (1) Two overly similar indicators in the secondary indicators were merged. Both indicators are related to the number of sports venues in Barcelona. (2) A secondary indicator "cultural and artistic facilities" was added. Considering that Barcelona's public art, such as urban sculptures, is the result of the urban renewal policy of "combining art and community development" since the end of the 20th century, it is one of the main features of the city's appearance and an important way for preschool children to get in touch with art, understand the city, and establish a sense of identity.

The adaptively adjusted evaluation system (Figure 3) is divided into 5 first-level indicators and 16 second-level indicators, namely: diversity of children's recreational facilities (12 points), nature (5 points), park scale (3 points), maintenance level (3 points) and safety (3 points), with a total score of 26 points. Among them, the "diversity of children's recreational facilities" with the highest weight emphasizes the importance of structural facilities suitable and attractive for children to play and the inclusiveness of urban parks, and it is also a group of indicators that mainly reflects the special needs of children. Many studies have shown that access to green and natural areas can have a positive impact on children's physical and mental health, so the indicators in "nature" are included to measure the ability of urban parks to provide children with opportunities to get close to natural landscapes, reflecting the ecological service capacity of parks. "Park scale" is an important part of the park's service capacity, but not its entirety, as is also reflected in the weight. The indicators "maintenance level" and "safety" are both at the management lev-

el, reflecting the soft quality of urban parks in serving children, and are a supplement to the aforementioned hardware evaluation. The weights of each indicator after adjustment were determined by the Analytic Hierarchy Process (AHP) combined with expert scoring. Experts in the fields of landscape architecture, child-friendliness, urban planning, and park management were invited to score the weights of each indicator through a questionnaire. The YAAHP software was then used to construct a hierarchical model for the scoring results. After consistency testing, the weight values of each indicator were finally obtained, and the results were highly similar to the weights of the reference scale.

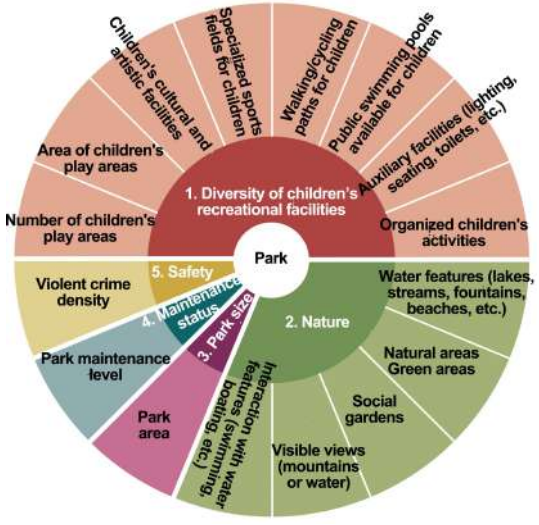

Figure 3 Child-oriented park quality evaluation scale

In terms of data sources, some indicators of the first, second and fifth categories in Figure 3 were collected through remote sensing images, online pictures, and supplementary field surveys. The scale of the park in the third category was obtained based on municipal statistical data. The maintenance level in the fourth category was scored according to the Barcelona Park Environment Standard. The violent crime density indicator in the fifth category was scored according to the crime rate data of the park area officially published.

Regarding the accessibility analysis of urban parks, this study used spatial syntax calculations based on the road network data around the urban park and selected a line segment model optimized on the basis of the axis model. The advantage of this model is that it fits the research of urban scale and considers the influence of spatial coordinate information and road length [22]. The depthmap 10.0 software developed by UCL was used in conjunction with the GIS analysis platform to measure the integration of the road network, reflecting the potential of a space to attract traffic. The integration is the inverse of the total depth. Global depth refers to the cumulative value of all topological depths from the central space to any other space after spatial remapping. The more topological steps a space needs to take to reach other spaces, the lower its accessibility. Therefore, the higher the integration, the higher the accessibility. Integration can be screened according to different radii, i.e., radiation ranges, and a commonly used walking radius of 500m was selected for local integration calculation based on the usage characteristics of preschool children [20, 21]. It was verified that it had a good fit with thevisitor number after standardization, so it was used as the range of local integration.

2.3 Data preparation

The research object is the urban parks managed by the Barcelona City Council, with a totalnumber of 159 (Figure 1). As shown in Table 1, this study obtained land use and sociodemographic data in 2018 through the Barcelona official statistics network. Open-source GIS data such as administrative boundaries, parks and road networks came from open-source maps and open urban databases.

Table 1 Data attributes and sources

Data category	Data category	Data year	Data sources
Urban statistics	Administrative area	2018	Barcelona Statistical Yearbook
	Urban park area	2018	Barcelona Statistical Yearbook
	Population of different ages	2018	Barcelona Statistical Yearbook
	Number of violent crimes	2018	Catalan Government Portal
Geospatial information data	Remote sensing data	2019	Google Maps
	Spatial vector data	2019	OpenStreetMap
	Road network vector data	2019	Barcelona open database(Carto BCN)
Online data	Real-life park map	2019	Google Maps and Facebook

3 Analysis results

3.1 Results of thechild-oriented quality evaluation of parks

According to QUINPY, the quality of 159 urban parks in Barcelona was evaluated. In terms of the first-level indicator"diversity of children's recreational facilities" (12 points), about 79% of urban parks in Barcelona have recreational spaces for children, most of which are slides, swings, seesaws and comprehensive recreational facilities. At present, there are not many stadiums that combine special sports to parks. Due to venue restrictions and other reasons, most sports facilities are simple fitness equipment and table tennis tables. More than 50% of the parks are equipped with cultural and artistic facilities, such as small art museums and galleries. The most distinctive public art installations are mainly sculptures, such as the sculpture "Woman and Bird" donated by local art master Joan Miró in his eponymous park, and the land art landscape "Sinking Sky" in the North Station Park, which provides a way for preschool children to recognize local cultural and artistic characteristics. In addition, more than 90% of the parks provide supporting facilities such as seats, lighting, picnic spots or washrooms, making it more convenient and comfortable for parents to accompany their children in activities in the park, which helps children and families establish a healthier interactive relationship. Only less than 16% of the parks in the city have organized children's activities, and the richness of participation and multi-group interaction of children when using parks need to be improved. In the "nature" part, most parks have good greening. The natural geographical location of the city with mountains behind and the sea in front makes many parks enjoy good vegetation and landscape resources, but there are fewer interactive landscapes. The scale of the park and the safety of the surrounding communities vary greatly, and the overall maintenance level is high. Therefore, from the above perspectives, a good foundation has been laid in terms of child-friendliness oriented quality of urban parks, but there is still room for improvement.

The overall QUINPY score of Barcelona's urban parks ranges from a minimum of 5 points to a maximum of 22 points, with an average of 11.57 (standard deviation of 3.76) and a median of 11. According to the score, the 159 urban parks are further divided into six categories by the natural break method (Figure 4). As shown in Figure 4, there are fewer parks in the old city and expansion area in the central part, especially the quality of parks in the expansion area is also low, and there are more parks in the north near the mountains and the south near the coastline, where the general quality of parks is higher. This spatial distribution feature is related to the development process of Barcelona. The old city began to be built since the Roman period, with flat terrain being the priority [23]. As a result, the area has a high building density and few green open spaces. In the modern historical city protection planning, the original form and pattern have been basically retained, so no large areas of green space have been added. The expansion area was planned and constructed in the mid-19th century, using a grid texture [23]. Many open spaces are located inside enclosed blocks. In addition, due to the rapid population growth in 1932, the planning of the original green space system was neglected to a certain extent, and large-scale construction occupied the green space of parks. Therefore, there are few large comprehensive parks in the built-up area of the expansion area. The areas near the coast and the mountains were developed later. During the new planning process, especially during the preparations for the Olympic Games, many large parks were built in the south [24], and their infrastructure was relatively complete. The communities in the west are close to the Collserola Mountains, and the communities in the east are close to the coast. Therefore, many high-quality parks have been created in combination with natural landscapes.

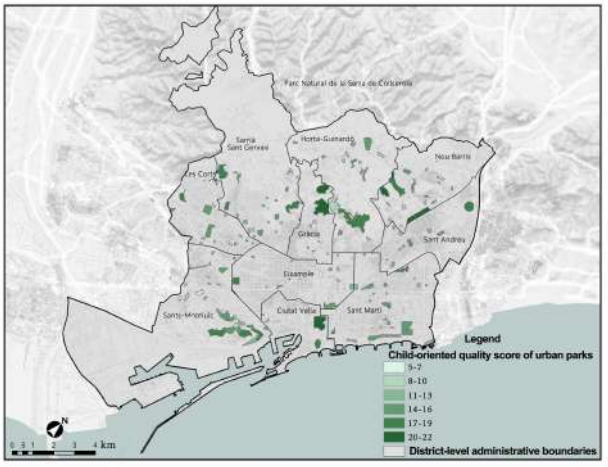

Figure 4 Child-oriented quality evaluation of urban parks

Based on the quality evaluation results, parks with different ratings, such as Joan Miró Park, Plaça de la Sagrada Família, Parc de l'Estació del Nord, and Parc de les Glòries, were selected for field research and interviews (Figure 5). Due to the limited expressive ability of preschool children, we conducted semi-structured interviews with the caregivers of preschool children who use urban parks, referring to the interview methods of existing studies [25, 26], to understand the users' satisfaction with the quality of the parks from a subjective perspective. In general, the QUINPY evaluation results are consistent with the subjective perceptions of the interviewed preschool children and their caregivers, further verifying the the quality evaluation results.

Figure 5 Park research interviews in Barcelona

3.2 Results of urban park accessibility analysis

The official open-source road network data was manually corrected, and 30,505 pre-processed urban road segments were imported into theDepthmap software and converted into segment models that can be analyzed. After passing the Node Count verification, the angle analysis calculation command was input, and the local integration results were output with the segment length as the weight. The buffer zone within the 500m service radius of parks in Barcelona was intercepted in GIS [21]. Based on the calculation results of the local integration (Figure 6), the accessibility of the parks was obtained through software statistics and mathematical calculations. The values ranged from 32.4 to 156.71, which were divided into six categories according to the natural break method (Figure 7). As shown in Figure 7, parks with high accessibility are mostly located in the city's geographical center extension area, as well as the coastal old town and Sant Martí district. The three main roads in the city: Diagonal Avenue (AV. Diagonal), Meridiana Avenue (AV. Meridiana) and Gran Via Avenue (AV. Gran Via) are the main factors for the high accessibility of parks in this area. The regular and walkable road network also increases the opportunity potential of parks in this area. Take the Plaça de la Sagrada Família, which has the highest accessibility level, as an example. It is close to the main roads of the city, with a high density of surrounding road networks and excellent walkability. It is very convenient for preschool children to enter the park. Low-accessibility parks are located in areas of the city close to mountains and coasts, such as Parc Güell, designed by the architect Gaudi, which is located on the edge of the city and has a limited density of surrounding road networks. It is less convenient for preschool children to enter the park.

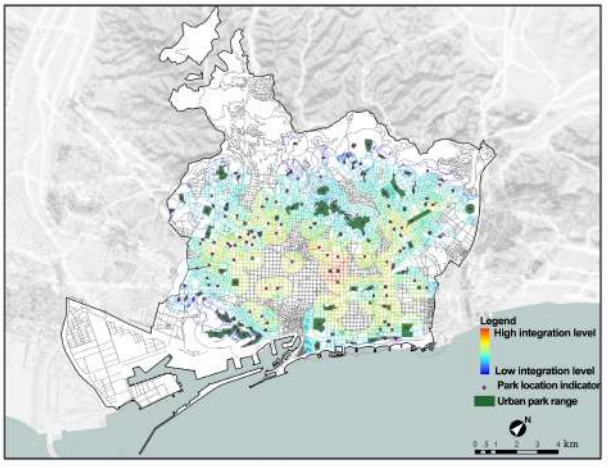

Figure 6 Local integration of roads within the buffer zone

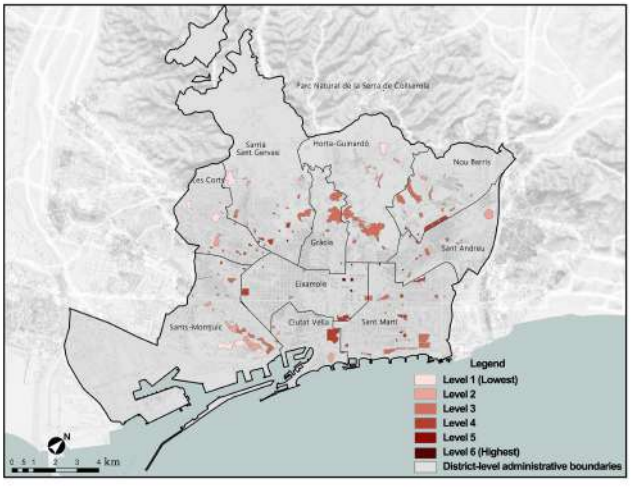

Figure 7 Accessibility classification of urban parks

3.3 Results of superimposed analysis of child-friendly quality and accessibility of urban parks

Based on the analysis results of the two dimensions

of child-friendly quality and spatial accessibility, this study further superimposed the analyses to comprehensively evaluate the internal use potential and external attraction potential of parks for preschool children, and then explore the specific advantages and disadvantages of parks in terms of function and layout. The superimposed analysis uses the classification results of the quality and accessibility of parks in the whole city as the boundary of "high quality-medium quality-low quality" and "high accessibility-medium accessibility-low accessibility," and constructs a 3 * 3 matrix for park evaluation according to the grounded theory attribute classification method. Since parks in Barcelona have a good foundation for overall quality and accessibility, and the focus of transformation and improvement is on low-quality and low-accessibility parks, "high quality" and "medium quality" as well as "high accessibility" and "medium accessibility" are further merged to obtain four major types of parks: higher quality/higher accessibility, higher quality/low accessibility, low quality/higher accessibility, and low quality/low accessibility (Figure 8). In addition, the evaluation results were further superimposed with the population density of preschool children in 73 neighborhoods in Barcelona, attempting to preliminarily explore the fairness of child-friendly distribution of parks in combination with the actual demand.

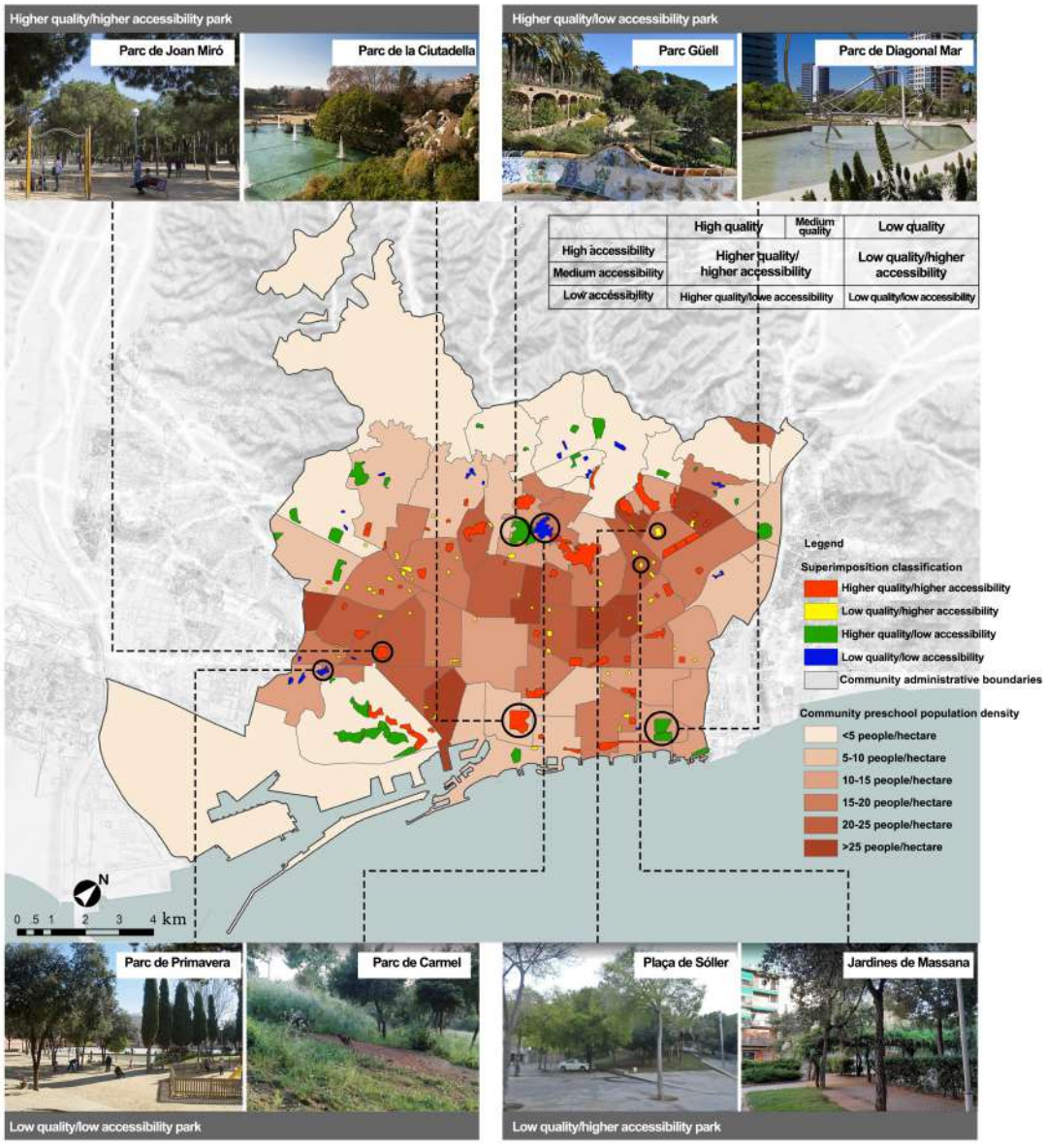

Figure 8 Superimposed analysis of park quality and accessibility

(1) Higher quality/higher accessibility

As shown in Figure 8, the number of such parks accounts for about 35% of the total. In terms of quality, such parks can provide convenient and high-quality services for preschool children. Most of them are well-known, historic, and large parks. As the city's business card and important attractions of the tourist city of Barcelona, they have received preferential treatment in terms of municipal funds and management. Such parks have good accessibility. On the one hand, they are mostly located on the sides of the Meridiani Avenue, one of the main traffic axes of the city, and on the other hand, they are located in the periphery of the expansion area with a well-developed road network and in high-income areas. The superimposed analysis of the child distribution density in the urban area of Barcelona shows that the child density in the areas where such parks are located is also high, which is more in line with the actual demand for children.

Among them, the more typical ones are Parc de la Ciutadella and Parc de Joan Miró. Parc de la Ciutadella (Figure 9) located in the central urban area was built in the late 19th century. It was converted from a military castle during the historical period when industrial land occupied a large amount of urban space. It has become a rare large park in the city center, accommodating various leisure and cultural activities suitable for children. The park received full marks in a first level indicator, the diversity of recreational facilities. In addition to complete supporting facilities and three well-equipped children's play areas, the castle architecture and sculptures representing the history of Catalonia allow children to be exposed to nature while also being influenced by history and art. At the same time, the "nature" indicator score is also high, mainly because the park has an open water surface for playing and boating. The modern-style Parc de Joan Miró (Figure 10) is equipped with six different types of children's activity spaces, which are concentrated on the open sand on the southeast side of the park, three of which are separated by fences and three are open. There are spaces composed of a single large complex children's recreational facility, as well as spaces composed of multiple facilities; there are unified signs outside the area, indicating the applicable age.

At the current stage of urban renewal, it is difficult to open new large-scale high-quality parks in areas with good accessibility. Therefore, such high-quality and highly accessible parks are scarcer. We should focus on maintaining their good service level and maintenance management to make them more effective.

(2) Lowquality/higher accessibility

This type of park accounts for about 32% of all parks in this study. The main reason for their low quality is the small area, which means the corresponding facilities and natural landscapes that can be accommodated are also relatively limited, and the service satisfaction provided to children is low. However, their accessibility is good, and they are mostly scattered in areas with convenient transportation such as university towns and expansion areas. By superimposing it with the density distribution of preschool children, it can be seen that such parks are often located in areas with high child density and high demand, so such parks have great transformation potential.

Among them, the more typicalJardines de Massana and Plaça de Sóller are both small-scale parks serving a community. Comparing the quality indicators of these two parks with the first-class high-quality/highly accessible Parc de la Ciutadella and Parc de Joan Miró after normalization (Figure 11), it was found that their main disadvantages are the lack of dedicated children's play areas, insufficient diversity of recreational facilities, and weak natural environment. Under the limitation that the park area cannot be expanded, one solution is to explore the possibility of increasing space utilization and functional diversity through three-dimensional design, such as referring to the design of the open space near the Rotebro Stadium in Sweden (Figure 12-a, 12-b), making full use of the wall to expand the activity space, and accommodating multifunctional children's facilities in a small place. The second way of improvement is to explore the multi-time composite function of limited space, serving multiple purposes by simple layout changes at different times, like the Chess Park in California, USA (Figure 12-c, 12-d), which is also a small venue. It provides a place for playing chess and resting during the day and a small movie theater at night. At the same time, its small open stage and multifunctional

wide seats also provide children with a multi-purpose space for performances and creative activities.

Figure 9 Parc de la Ciutadella plan and real scene photos

Figure 10 Parc de Joan Miró plan and real scene photos

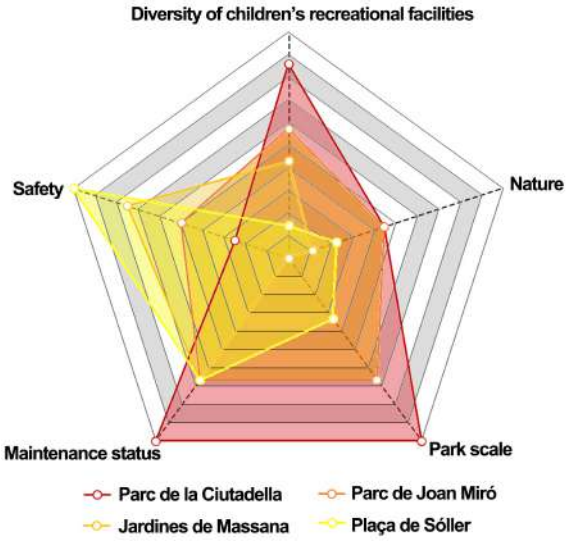

Figure 11 Child-friendly quality evaluation of two types of parks

Figure 12 12-a, 12-b Real view of open space nearRotebro Stadium in Sweden and functional zoning; 12-c, 12-d Real view of Chess Park in California, USA

(3) Higher quality/low accessibility

This type of park accounts for about 20% of the total, including famous parks such as Parc Güell and the park near the Montjuïc that was renovated before the Olympic Games. The high quality of this type of park is reflected in their large area, good natural landscape, open space and rich structural facilities, and they are located in a community with good public security. However, in terms of accessibility, due to their relatively marginal distribution and sparse road network, they cannot conveniently serve children in the surrounding area despite their high quality. There are relatively few children in the surrounding area, and the demand is not high. However, as a type of park with a large area and high carrying capacity, they can consider sharing the needs of children across the city, thereby improving the efficiency of park space use. It is recommended that, while reasonably improving walking accessibility, more bus routes should be added or public

transportation fees should be reduced or exempted at different time periods to encourage some families who live far away to bring their children to such parks on weekends; the service frequency of public transportation should be reasonably increased to strengthen the transportation connection with densely populated areas, so that people including preschool children can reach and visit this type of parks more conveniently.

(4) Low quality/low accessibility

This type of parkamounts to about 13% of the total. They have neither good accessibility nor the ability to provide good services for children. Parks in this category need to be improved in many aspects during the renewal. From the perspective of quality evaluation, the score results of the first-level indicator "diversity of recreational facilities" show that there is no shortage of recreational areas in such parks, but there are almost no organized children's activities. Other major weaknesses are "safety" and "maintenance level," which reflect the "soft power" of the park. The low accessibility is due to the fact that most of them are distributed in areas with inconvenient transportation on the edge of the city, such as the Horta-Guinardó district in the northwest. Combined with socioeconomic indicators, in the communities where such parks are concentrated, the child density is mostly not low, while the income index is in the middle and lower reaches of the city. Therefore, from the perspective of fairness in resource allocation, more efforts should be made to improve their service capabilities.

4 Conclusion and outlook

This study takes child-friendliness as the starting point, attempts to construct an evaluation framework that integrates park quality and accessibility analysis, and conducts a corresponding evaluation and diagnosis usingurban parks in Barcelona, Spain as a case study. In terms of evaluation methods, combining park quality evaluation with accessibility analysis based on geographic information data provides a relatively fast and direct method for measuring the child-friendly service level of parks at the urban scale, and provides a certain basis for subsequent improvement and optimization. Given the universality of geographic information data sources, this analysis framework can be quickly applied to the analysis of other urban cases.

In terms of empirical analysis, the quality evaluation results ofurban parks in Barcelona based on QUINPY show that regarding spatial distribution, high-quality parks are less in the middle of the city and dense at the edge, which is closely related to the city's topographic conditions and construction and development process. The accessibility evaluation results show a trend of gradually weakening from the city center to the edge. Improvement measures need to be combined with the needs of children in each community, so this study further superimposes the child population density for analysis and attempts to take the fairness of distribution into consideration. Combined with specific indicator scores, it is recommended that the improvement of park quality be combined with improving urban governance and park maintenance levels. Barcelona's city parks are uniformly managed, constructed, renovated and maintained by the Municipal Parks and Gardens Institute of the City Council. The maintenance and management funds are uniformly allocated throughout the city, and the organization formulates a uniform budget. Therefore, parks with high demand and low supply can be the focus of municipal funding and management improvement. Specific measures include maintenance and renewal of relevant facilities, environmental cleaning, optimization of the configuration of natural elements such as greenery. At the same time, public safety management should be strengthened to improve safety and provide a more secure environment for children to travel and play outdoors. In the case of limited funds, the public can also be encouraged to participate in enhancing resident autonomy. For example, an autonomous organization for the use of children's parks can be established in the community to mobilize the power of residents. It can not only help each other maintain the environment and safety of the park, but also organize a variety of children's activities, thereby improving the child-friendly service quality of the park space.

Our country has entered a period of stock development, shifting from focusing on quantity to pursuing quality, prioritizing people and social justice, and child-friendliness is becoming one of the focuses of urban construc-

tion. The evaluation framework built in this study with preschool children as the research object can help designers and managers clearly diagnose the relevant advantages and disadvantages of urban parks in macro layout and micro design, and then formulate more targeted improvement plans. Based on the "quality-accessibility" evaluation, we can further refine the balance between children's needs and park supply in the future, not only from the perspective of distributive justice, but also from the perspectives of procedural justice and interactive justice [27] to optimize the fair design and governance of landscapes for children. Besides adding structural facilities, the improvement strategies adopted based on the evaluation results can also encourage appropriate innovative measures, such as using the site in different time periods, expanding the possibility of space use by three-dimensional design, and actively exploring residents' self-organization. Barcelona is developing a shared campus strategy, attempting to supplement the public green space available for preschool children to play by establishing a shared campus partnership with educational and private institutions and opening the campus at appropriate time periods. In general, improvement plans based on the evaluation results need to take into account both suitability and operability, and mobilize and integrate multiple forces to improve the child-friendliness and landscape justice of urban parks.

Figure and table sources

Figure 1: adapted from the report"Social and Environmental Services of Barcelona Green Spaces"

Figures 2 and 3: drawn by the author

Figures 4, 6-8, 11: drawn by the author based on the analysis results

Figure 5: taken by the author

Figures 9 and 10: adapted by the author based on documents on the official website of the City Council

Figure 12: adapted by the author based ononline pictures (URL: http:// www.archdaily.cn/; http:// wbla-hk.com/content/view? id= 381)

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Review on the Research of the Relationship between Residential Landscape and Elderly Health

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ABSTRACT: The landscape of residential is closely related to the physical and mental health of the elderly. With the increasingly aging society, how to build a healthy living environment for the elderly is one of the important issues that need to be studied. Using scientific metrology tools such as CiteSpace to conduct knowledge map analysis on relevant literature, the research trends of the relationship between residential landscape and the health of the elderly were systematically summarized. The results showed as follows: 1) The number of domestic and foreign studies has been increased significant during the past 10 years. The research areas are mainly distributed in the fields of public health and geriatrics in foreign countries, while the domestic is mainly in the fields of architecture science and sports;2)Residential landscape factors and their mechanisms that affect the health of the elderly have been the research hot spot in both domestic and abroad. In terms of landscape elements of residential, most of studies focused on green space, water body and sensory environment, while in mechanism focused on physical activity, autonomous needs and social cohesion.3) The existing research mainly uses the subjective and objective measurement methods such as questionnaire, health benefit scale, objective measured environment and physiological indicators measurement. The trend is gradually shifting from the qualitative approach to the combination of qualitative and quantitative methods. The current study would provide evidence for future research and practice of age-health residential landscape.

KEY WORDS: residence; landscape environment; elderly health; CiteSpace

Introduction

In recent years, our country's aging population has shown complex characteristics such as "getting old before getting rich," "getting old before being prepared," and " getting arrogant before getting rich." Problems such as aging, empty nesters, and disability have continued to increase the burden of elderly care for the whole society [1-2]. As the aging population deepens, how to achieve " healthy aging" has become an important issue for academic research [3]. In the context of vigorously promoting community-based elderly care, home-based elderly care, and institutional elderly care [4], the living environment will become an important factor affecting the health of the elderly. A large number of studies have shown that the landscape elements in the living environment are closely related to the physical and mental health of the elderly. The outdoor environment of the residential area is a place

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for the elderly to experience nature, socialize, relax, exercise, and engage in other activities [5-6]. A good outdoor environment in the residential area can improve the physical function of the elderly, improve sleep quality, relieve stress, and maintain a positive emotional state [7-12]. Therefore, creating a living environment conducive to improving the health benefits of the elderly is an important topic that needs to beapproached from such perspectives as planning, architecture, and landscape architecture.

At present, with the increasing attention paid to elderly-friendly landscapes, relevant review literature has also begun to emerge in China, mainly involving urban environment, community environment, elderly care environment, rehabilitation gardens and architectural environment. For example, Dou Xiaolu et al. reviewed the current status of the construction of elderly-friendly cities in the West and summarized its standards and specific construction cases [13]. Yu Yifan et al. conducted a systematic analysis of the distribution, research history and research key points of international research on elderly-friendly environments, and clarified that "health" is the core issue in this field [14]. Many scholars have also systematically reviewed the development trends of elderly-friendly communities at home and abroad [15-16]. In the field of rehabilitation landscape research, Wang Shengfei et al. introduced the application of rehabilitation landscapes in foreign elderly care environments and analyzed the current status of planning and design of elderly care rehabilitation landscapes in China [17]. Sun Zhenning et al. summarized the needs for outdoor space of dementia patients, as well as their independent mobility, preferences and safety, and systematically sorted out the theoretical and practical experience of dementia rehabilitation gardens in the United States [18]. Although there have been review studies based on different perspectives, there is still a lack of reviews on the relationship between residential landscape environment and the health of the elderly. At the same time, with the extensive development and deepening of relevant research in recent years, it is very necessary to further sort out and summarize the existing research in this field in a systematic manner.

Based on this, in order to clarify the relationship between the landscape environment of residential areas and the health of the elderly, this paper uses scientific measurement tools such as CiteSpace to analyze the knowledge graph of literature data based on the search results in the Web of Science (hereinafter referred to as WOS) core collection and China National Knowledge Infrastructure (CNKI) database, systematically sorts out the development trends and research hotspots in this field, summarizes the existing research content and methods, and provides a reference for the research and practice of domestic elderly-friendly healthy living environment.

1 Literature sources and research method

1.1 Data collection

The English literature datacame from the WOS core collection. In order to cover the research field as much as possible, after adjusting the search strategy several times, it was finally determined to use TS = (residential OR neighborhood OR community) AND (landscape OR green space OR outdoor OR garden OR park OR greenness OR nature) AND (elderly OR old people OR elderly people OR senior citizen* OR elderly adult) AND (health OR well-being OR therapeutic OR restorative) as the search formula for retrieval. The search field was the title, the language was "English", the document types were "Article," "Proceeding Paper" and "Review," the time span was "1999-2021," and the search time was February 18, 2021. There were 725 search results in total.

The Chinese literature datacame from CNKI, and the search was carried out with "residential area" (or including "residential area" or "community"), "landscape" (or including "outdoor," "green space," "green land," "landscape environment," etc.), "elderly" (or including "aging," "suitable for the elderly," "elderly care" or “old people”) and "health" (or including "rehabilitation", "fitness", "health care", "healing", "recovery", "mental health", etc.) as keywords. The search field was the title, and the time span and search time were the same as above. The search results were 456 in total. After reading the search results one by one, items such as news and conference notices were removed, and a total of 365 Chinese articles were screened.

1.2 Visualization analysis method

The built-in analysis tools of CNKI and WOS, scien-

tific text mining and visualization software CiteSpace and Graphpad Prism were used to conduct quantitative visualization analysis of the literature. First, the database built-in analysis tools were used to count the annual number of domestic and foreign literature and related domestic disciplines; then CiteSpace was used to analyze and mine related domestic and foreign literature, and visualize the discipline distribution, keywords, and co-citation of literature, in order to clarify the research status and development trend of this field.

2 Overview of domestic and foreign research

2.1 Trends in the number of research studies

The annual distribution and trend of the number of research papers can better reflect the importance of this field and the degree of attention it has received. The 725 English papers and 365 Chinese papers retrieved were statistically analyzed. From the perspective of the number of papers published and the trend of change, the number of papers in this field is increasing as a whole. Relevant research has appeared in foreign countries since 2002, and the number of Englisharticles has shown a continuous upward trend since 2009. However, the early research progress in China was relatively slow, and the number of Chinese papers has gradually increased since 2012. In general, with the deepening of social aging and the increasing number of healthy environmental studies, domestic and foreign scholars have begun to pay more and more attention to the relationship between residential landscape environment and elderly health in the past decade.

2.2 Distribution of research disciplines

The distribution of English literature in disciplines was analyzed using CiteSpace. The resultsshow that public, environmental & occupational health is the discipline with the most research papers published abroad, indicating that this discipline occupies an important position in foreign research in this field. Secondly, geriatrics & gerontology, environmental sciences & ecology, and psychiatry are the main research disciplines in this field. The statistical results of the literature search results using CNKI's analysis tools show that the range of domestic research disciplines is relatively wide in this field, among which architectural science and engineering make up the largest proportion, accounting for 68.6%, followed by sports, Chinese politics, international politics, etc.

2.3 Analysis of main research hotspots

Keywordsreflect the author's refinement and summary of the main content of the article, and keyword co-occurrence analysis shows the research hotspots and research frontiers in this field. Literature co-citation analysis can sort out the branch structure and evolution context of the research field, and co-citation network clustering analysis can reveal the research frontiers in this field. With the help of CiteSpace, the keyword co-occurrence network map of domestic and foreign research is obtained. Since CiteSpace cannot perform literature co-citation analysis on Chinese literature, it only generates a co-citation literature clustering timeline map and a structural clustering map for English literature. The co-occurrence network map shows that foreign research mainly focuses on built environment, neighborhood, mental health, quality of life and depression. The results of network clustering map analysis show that the main clusters are physical activity, social cohesion, social isolation, green space and neighborhood disorder. Relevant research focuses in China mainly include rehabilitation landscape, retirement community, aging-friendly transformation, horticultural therapy, integration of medicine and nursing, design strategy and physical activity. In summary, it can be found that the research hotspots are mainly concentrated in two aspects: "residential landscape elements from the perspective of elderly health" and "the mechanism of the impact of residential landscape environment on the health of the elderly."

3 Main contents and methods of research on landscape environment and elderly health in residential areas

3.1 Landscape elements of residential areas from the perspective of elderly health

3.1.1 Green space landscape

Green spaces in residential environments can promote the physical and mental health of the elderly by improving environmental conditions and providing ecosystem and environmental service functions. Green space landscape indicators that affect the health of the elderly can be divid-

ed into levels such as green space site attributes, green space accessibility, and green space vegetation characteristics. Research on living environment and aging health shows that green space attribute indicators such as green space type [19], green space quantity [20-21], green spaceratio [22-24], per capita green space area [25], green space accessibility indicators like the distance between green space and residence [26-27] and green space vegetation characteristic indicators such as visible green index [28], the normalized difference vegetation index (NDVI) [29-31], enhanced vegetation index (EVI) [32-33], the three-dimensional amount of greening [34] and the perceived evaluation of vegetation quality [35-36] will significantly affect the health of the elderly (Table 1). The above studies have involved many health-related indicators for the elderly, such as myoelectricity, mental fatigue recovery, mortality, cardiovascular morbidity, depression, positive emotions, etc. For example, an Australian study pointed out that the mortality rate of elderly residents with a high average greening rate within 300m of their residences was 9% lower than that of elderly residents with low greening rates around their residences [21]. Some studies have also shown that a higher greening rate in residence can delay the decline of walking ability and grip strength of the elderly [33]. Current research mostly uses the NDVI or green space ratio to measure the green space landscape in the residential environment. These indicators are not enough to fully express the quality of the green space landscape, and it is difficult to describe the perceived experience of and benefits from using green space by elderly residents based on them. Therefore, more refined indicators from the human perspective, such as visible green index, vegetation diversity, and vegetation canopy density, should be used to study the impact of residential area green space landscape on the health of the elderly. Although environmental indicators used for quantitative research are becoming more and more comprehensive, the following questions remain unresolved: To what extent do the spatial composition, density, vegetation types, smell, shape and other detailed characteristics of green space landscapes affect the health of the elderly? How to scientifically evaluate the green space landscape design in residential areas that is beneficial to the physical and mental health of the elderly?

3.1.2 Water features

Water features can affect physical health by increasing negative ion concentration, reducing noise, and promoting activities, and it also has the effects of relieving stress, improving mood, eliminating fatigue, and promoting mental health; it can even create a rich spatial atmosphere to support social activities [37]. Some articles have confirmed that water features can effectively promote the health level of the elderly [38-40]. Garrett et al. found in Hong Kong that the elderly who can see water feature space from their homes are more likely to have good overall health, and frequent contact with water feature space is associated with higher subjective well-being or lower depression [41]100. Some studies have pointed out that the per capita water feature area can affect the mental health of the elderly by reducing environmental pollution, relieving stress, and promoting social interaction. Water features can bring a cool feeling in hot weather. Walking along the waterside and sitting quietly can reduce cortisol levels and make the elderly feel happy, although the water feature environment in the living environment has limited effect on promoting physical activity of the elderly [42]. The characteristics of water feature tranquility, shelter, and vastness can restore the spirit of the elderly [43]. However, some studies have shown that the elderly believe that water features in the outdoor environment of residential areas may be harmful and that they are not essential for outdoor activities [44]11. Therefore, the health benefits of water features in residential areas and their cognitive effects on the elderly need further in-depth research.

3.1.3 Sensory environment

The sensory environment of a residential area refers to the sound environment, olfacory environment, and environmental factors such as wind, light, and heat that can make the elderly feel comfortable. Good sensory experience in the environment has a positive effect on the physical and mental health of the elderly. For example, studies have found that bird sounds can effectively enhance the elderly's pleasant emotions and sense of quietness [45]. At the same time, due to reduced immunity, the health of the elderly is easily af-

fected by the thermal environment. They believe that good ventilation and avoiding the hot sun are essential [44]1, and there is a strong correlation between the comfort of the spatial wind, light, and heat environment and the elderly's leisure and entertainment activities [46]. In creating a sensory experience in the residential environment, the visual needs of the elderly can be met by utilizing space, sight, color, light and shadow, the needs for auditory experience can be met by introducing comfortable natural habitats, adding artificial soundscapes and eliminating noise, the olfactory needs can be met by creating scented landscapes, the tactile needs can be met by combining animals, plants and water features, and the elderly can be allowed to grow edible plants by setting up participatory gardening landscapes, which can satisfy their visual, tactile, olfactory or taste experiences in the process of cultivation, picking and tasting [47].

Table 1 Research on the correlation between green space landscape in the residential environment and elderly health

Category	Specific indicator	Health-related indicators	Mainconclusions
Green space attribute indicators	Green space type	Recovery of electromyographical and mental fatigue	The relaxing effect of mountain and forest landscapes is the most obvious, followed by lawn landscapes, and the effects of water bodies, farmland and wetlands are relatively weak [19]
	Green space scale	All-cause mortality	There is no significant correlation between park size and all-cause mortality [21]
	Green space quantity	Social health, mortality	There is a negative correlation between the number of parks and social health [20]; there is a significant correlation between the number of natural spaces within the 500-meter buffer zone and mortality [21]
	Green spaceratio	Self-assessed perceived health, diabetes incidence	Living in an area with park coverage of more than 8% is positively correlated with self-rated health [22]; green spaces have a positive impact on health [23]; elderly people who live in the greenest neighborhoods have a 19% lower risk of diabetes [24]
	Per capita green space area	Cardiovascular disease incidence	Compared with the elderly living in areas with low green space levels, the elderly living in areas with medium-low, medium-high, and high green space levels have significantly lower rates of cardiovascular disease [25]
Green space accessibility indicator	Distance between green space and residence	Perceived physical health	The perception of the distance to parks is a prerequisite for park use, daily physical activity and health [26]; the elderly participate in more nature-related activities, so the distance of green spaces from them should not be too large [27]
Green space vegetation indicators	Visible green index	Depression	Visible green index is negatively correlated with depression[28]
	Normalized difference vegetation index	Diagnosis rate of heart disease, body mass index (BMI), all-cause mortality, circulatory system mortality, stroke mortality	More greening can reduce the risk of myocardial infarction, ischemic heart disease, heart failure and atrial fibrillation [29]; there is an inverted "U"-shaped relationship between greening and BMI. When the level of greening is low, BMI increases with greening. When the greening level is high, BMI decreases with increasing greening [30]; the higher the green space coverage, the lower the all-cause mortality, circulatory system mortality and stroke mortality in the elderly [31]
	Enhanced vegetation index	Type 2 diabetes incidence, walking ability	Residential greening affects fasting blood sugar levels and walking ability decline in the elderly [32-33]
	Three-dimensional amount of greening	Health-related ecological service functions	The three-dimensional amount of greening is significantly correlated with the air negative ion concentration, temperature, and humidity. The tree layer and ground cover layer are significantly correlated with temperature, humidity, and negative ions [34]
	Perceived evaluation of vegetation quality	Life satisfaction, meaning of life, positive emotions	There is a significant positive correlation between the perceived evaluation of vegetation quality and life satisfaction, meaning of life, and positive emotions [35-36]

3.2 Mechanisms of residential landscape environmentaffecting the health of the elderly

3.2.1 Promoting physical activity

A sedentary lifestyle can lead to common chronic diseases in the elderly, including cardiovascular diseases, diabetes, obesity and depression [48]. Empirical studies have shown that physical activity can provide important health benefits for the elderly andthat walking for more

than 4 hours per week can effectively reduce the risk of cardiovascular disease [49]. Physical activity can also improve the symptoms of depression and loneliness in the elderly, improve the quality of life and happiness, maintain good cognitive function, and reduce the risk of falls, hypertension, stroke, and diabetes [50-51]. Studies have shown that the outdoor landscape environment in residential areas can further improve the health of the elderly by promoting their physical activity [52-53]. Elderly people who have green spaces near their homes are more willing to go out for activities [54-55]. Tan Shaohua et al. proposed a quality hierarchy of necessity, spontaneity, and sociality for the physical activity of the elderly, and found that a low-quality environment can only support "necessary" physical activities, while a high-quality environment can trigger the occurrence of "spontaneous" and "social" activities [56]. Environmental factors that are positively correlated with physical activity of the elderly include walkability, residential density, accessibility of facilities, beautiful scenery, good lighting, etc. [50]1. At the same time, the residential environment and physical activity have different effects on the elderly of different ages, so it is necessary to design an environment that promotes physical activity for different age groups.

3.2.2 Meeting the needs of autonomy

As their physical functions decline, the elderly are more likely to feel a loss of control over their lives. For the elderly, maintaining autonomy and independence not only means maintaining good functions at the physiological level and acting as they wish, but also means controlling their own lives at the psychological level, solving problems independently and making decisions [57]. The physical characteristics of the residential landscape play an important role in supporting or restricting the autonomy and independence needs of the elderly. A good supportive environment can enhance their sense of achievement and self-confidence in life, and positively affect their health, thereby indirectly reducing the pressure on public health services [58]. At present, most of the research on community-friendly design for the elderly focuses only on barrier-free design. Some existing problems cannot meet the diverse needs of the elderly for physical and mental health, such as unreasonable zoning of rest areas and lack of consideration for wind environment, shade, and lighting environment [59-60]. Increasing the travel options for the elderly, providing a variety of seating options, and guiding them to participate in public activities can effectively meet the needs of the elderly for independence.

3.2.3 Improving social cohesion

Social cohesion refers to the mutual trust, social connection, and solidarity among residents [61]. Social relationships can affect health through the following mechanisms: social participation, social support (perceived or actual), social influence (such as setting norms), access to information, and social connections [62]. For example, social cohesion can improve the health of the elderly by promoting the rapid spread of health-related information, stimulating social and physical exercise behaviors, reducing negative emotions, and influencing changes in the community environment [63]. Studies have found that community cohesion is significantly correlated with the elderly's daily living activities, depression, health awareness, and subjective well-being [64-66]. A German study pointed out that the elderly with close social networks use parks more frequently and are more likely to obtain health benefits [67]. Other studies have shown that the characteristics of the residential environment can affect the elderly's identification with the community and social cohesion, and community cohesion can mediate the relationship between the neighborhood environment and the elderly's life satisfaction, meaning in life, and positive emotions [35, 68].

3.3 Main research methods based on evidence-based design

At present, the methods used in domestic and foreign evidence-based investigations of the relationship between residential landscape environment and elderly health can be divided into subjective measurement methods and objective measurement methods (Table 2).

Table 2 Measurement tools and methods used to study the relationship between residential landscape environment and health of the elderly

Category		Measurement tools and methods
Subjective measurement methods	Environmental characteristics of residential areas	Perceived Residential Environment Quality Indicators, PREQI; Neighborhood Environment Walkability Scale (NEWS)
	Health level of the elderly	Positive and Negative Affect Schedule (PANAS), Kessler Psychological Distress Scale (K10), State-Trait Anxiety Inventory (STAI), Geriatric Depression Scale (GDS), WHO 5-item Well-being Scale (WHO-5), 36-item Short Form Health Questionnaire (SF-36), EuroQol Five-dimensions (EQ-5D)
Objective measurement methods	Environmental characteristics of residential areas	Geographic vector spatial data, remote sensing image data, street view data, field survey data
	Health level of the elderly	Electroencephalography, electromyography, blood pressure, heart rate, skin conductance, eye movement, functional near-infrared spectroscopy

3.3.1 Subjective measurement methods

Currently, a large number of studies use the Perceived Residential Environment Quality Indicators (PREQI) questionnaire developed by Bonaiuto and colleagues for subjective measurement of residential environment characteristics [35]83. This questionnaire includes four dimensions of neighborhood environment characteristics: architectural and planning features, socio-relational features, functional features and contextual features. As the role of residential environment in promoting physical activities such as walking behavior among the elderly has received increasing attention, the Neighborhood Environment Walkability Scale (NEWS) has been widely used. The measured environmental characteristics include mixed use of land, street connectivity, neighborhood facilities, pedestrian infrastructure, aesthetic characteristics, neighborhood safety, etc. [53]5. The former is a more comprehensive residential environment evaluation tool that includes evaluations of physical and social levels and is suitable for studies focusing on various types of indicators of residential environment quality, while the latter focuses mainly on the evaluation of the walkability of the physical environment of the residential area. Measuring the perceived evaluation of the residential environment through a scale can reflect the residents' experience or satisfaction, but compared with objective measurement, questionnaire surveys have problems such as subjectivity and sample cognitive bias. Common subjective measurement scales for the health level of the elderly include: The Positive and Negative Affect Schedule (PANAS) [35] 86, Kessler Psychological Distress Scale (K10) [69], State-trait Anxiety Inventory (STAI) [70], Geriatric Depression Scale (GDS) [71], World Health Organization 5-item Well-being Scale (WHO-5) [41] 102, 36-item Short Form Health Questionnaire (SF-36) [72], EuroQol Five-dimensions (EQ-5D), etc. Among them, PANAS, K10, STAI, GDS and WHO-5 scales are used to assess different emotional characteristics and mental health levels of the elderly, while SF-36 and EQ-5D scales are multidimensional health and quality of life measurement methods that can comprehensively assess physical, psychological and social health. Compared with the measurement of objective physiological indicators, the subjective health scale measurement method has the advantage of high operability, but it cannot present the real-time human-land interaction status and environmental health performance characteristics in the real time-space.

3.3.2 Objective measurement method

Based on existing research, it can be found that the data sources for objective measurement of residential environmental characteristics can be divided into four categories, including geospatial data (land use type, road network data, POI data, etc.), remote sensing image data (NDVI, EVI, green space ratio, etc.), street view data and field survey data (wind speed, humidity, temperature, etc.). The data volume of geospatial data and remote sensing image data covers a wide range, but people in the same spatial unit share the same environmental characteristics, and the research results may deviate from the actual situation. At the same time, since street view data can be obtained only for open compounds but not for closed compounds, the environmental features extracted from street views may not represent all types of residential areas. However, data collection for field surveys requires a lot of time and manpower, and it is difficult to obtain more large-scale data.

For objective measurement of the health level of the elderly, many studies have adopted non-invasive, minimally intrusive, and safe methods, such as measuring EEG, EMG, blood pressure, heart rate, skin conductance, functional near-infrared spectroscopy and eye movement activity [73-74].

4 Research evaluations and prospects

This paper reviews the relevant research on the relationship between residential landscape environment and the health of the elderly, which can provide reference for the systematic research and planning and design practice of the elderly-friendly healthy residential environment in the future, and is of great significance for alleviating the pressure of society to cope with aging and improving the welfare and quality of life of the elderly. A summary of existing research shows the following. 1) In terms of research methods, most foreign studies are quantitative studies of correlation exploration, mainly using cohort studies, sampling questionnaires, cross-sectional surveys and other methods. Most domestic studies are qualitative studies, and quantitative studies are relatively rare. Regarding the trend of development, domestic and foreign research in this field has gradually shifted from qualitative research to a combination of qualitative and quantitative research. 2) In terms of research content, domestic research started later than foreign research, and most of it focused on the design of elderly-friendly community environments, and there were relatively fewinterdisciplinary studies with the field of elderly health. In terms of exploring the mechanism of the impact of residential landscape environment on the health of the elderly, domestic and foreign research still lacks in-depth research on the specific elements of the landscape environment. 3) In terms of research indicators, although the indicators used to study the characteristics of residential landscape are becoming more and more comprehensive, most of them are concentrated on the study of green landscape and use a single indicator or a combination of simple indicators. The selection of indicators in subjective evaluation scales of the residential environment is mostly based on subjective experience, and there is a lack of research combining subjective and objective indices.

In summary, in the future, it is necessary to deepen the interdisciplinary cooperation and research content of the residential landscape environment based on the health of the elderly, build a more scientific evaluation system for the landscape environment of elderly-friendly healthy residential areas, and further explore the intrinsic impact mechanism of the residential landscape environment on the health of the elderly through quantitative analysis. In the field of practice, it is urgent to incorporate the concept of "elderly health promotion" into the planning and design of the outdoor landscape environment of residential areas, pay attention to improving the quality, accessibility, comfort and sustainability of the landscape environment at the micro level such as green space, water features, sensory experience, and create a residential environment dedicated to promoting physical activities of the elderly, meeting autonomy needs and improving social cohesion. At the same time, in the future, new research technologies and methods such as portable biofeedback instruments, machine learning, and big data analysis can be combined to collect massive environmental and health data, dynamically evaluate and manage the residential landscape environment at multiple scales to maximize its elderly-friendly health benefits. However, the restrictive conditions set during data collection in this study determined that its results had certain limitations. For example, only the CNKI and WOS databases were searched, and relevant literature from other databases was not included, resulting in an incomplete survey and room of improvement for similar studies in the future.

Figure and table sources

Tables 1-2: Created by the author based on the literature.

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Comparison of Domestic and Foreign Research on Natural Ventilation of Buildings Based on Bibliometric Analysis

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ABSTRACT: The outbreak of COVID-19 has made people pay more attention to the health performance of buildings. Natural ventilation plays an important role in improving the indoor air quality related to health. To reveal the research situation of research on the natural ventilation of buildings at home and abroad, we take the Web of science and CNKI's periodical literature about the natural ventilation research on buildings as the object of our research. Furthermore, we adopt the method of bibliometric analysis, and use the visualization function of the CiteSpace and VOSviewer tools. We systematically summarize the overall characteristics and evolution process of the research field. The analysis found that there are differences in research hotspots and trends in the field of building natural ventilation at home and abroad. The foreign research on the natural ventilation of buildings began earlier, and is richer and more detailed. Human health issues are the main concept throughout, with emphasis on air quality and human behaviour. In contrast, the related research in China began to be carried out late, and the overall research has shown the characteristics of decentralization, focusing on building energy conservation. Experiments and numerical simulations are the common research methods. The latest research attempts to introduce intelligent computer optimization technology to assist the natural ventilation of buildings in the design stage. Finally, summarizing the existing research results and put proposed research projects can provide the necessary basis and inspiration for research on building natural ventilation in China and contribute to the improvement of indoor air quality and the protection of the ecological environment.

KEY WORDS: natural ventilation; bibliometrics; CiteSpace; VOSviewer; research hotspots; research trends

Introduction

In 2020, a sudden COVID-19 pandemic swept the world, causing immeasurable losses to human society and exacerbating the global health crisis. The indoor environment where we live and work is the most common place for infectious diseases to spread. Existing studies have shown that effective natural ventilation in indoor environments can prevent the spread of infectious diseases [1], is beneficial to health, and the human body is more comfortable in a naturally ventilated environment than in an air-conditioned environment [2]. In addition, natural ventilation is the main passive strategy to reduce energy consumption by air conditioning systems. Therefore, while ensuring people's health and comfort, natural ventilation of buildings can effectively reduce building energy consumption and environmental pollution [3], which is of great significance to "Healthy China 2030"[1] and "China 2030 Carbon Peak"[2].

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In the past three decades, domestic and foreign scholars have carried out a series of studies on naturalventilation of buildings and published a large number of papers, which makes it difficult to grasp the research focus and status of natural ventilation of buildings. At present, most of the review articles on natural ventilation of buildings by domestic scholars are from a single perspective, such as technology [4], effect [5] and application [6]. At the same time, the existing research is mostly sorted by time, but the overall context comparison of domestic and foreign research is rarely included. Based on this, this paper uses bibliometric methods to conduct a visual analysis of the literature on natural ventilation of buildings at home and abroad, and sorts out and summarizes some classic literature to provide reference for in-depth research on natural ventilation of buildings in the future.

1 Research methods and data sources

1.1 Research methods

This paper uses CiteSpace and VOSviewer as bibliometric tools. Both software can analyze the clustering and evolution of literature keywords, but each has its own characteristics. VOSviewer can present research hotspots through beautiful and clear color blocks; CiteSpace is better at keyword mutation analysis which displays research context and evolution process, convenient for mining recent research frontiers of disciplines.

1.2 Data sources

The Chinese and English literature sources are CNKI and Web of Science respectively, and the search time is from January 1, 1990 to December 31, 2020. In order to comprehensively collect relevant literature, literature retrieval is carried out in the followingsteps [7]. 1) Direct search: Professional terms "natural ventilation, single-side/side/direct ventilation, cross/convection/two-way ventilation, wind through-the-hallway wind" and "building" in Chinese, and "natural ventilation, single-side ventilation, cross ventilation" and "building" were used in combination for advanced subject search. 2) Retrospective search: In the literature retrieved in the previous step, similar related keywords, including "residence, office, large space, gymnasium" in Chinese and "residen* , office* , university* ", etc., were used for retrospective search. 3) Circular search: The search in the first two steps was circulated to include highly relevant literature. A total of 3,049 Chinese pieces were obtained using CNKI "all journals" as the source, and a total of 4,068 foreign literatures were obtained using the core set of Web of Science "all journals" as the source. Among them, 569 Chinese and 466 foreign pieces were from "important journals" in the field of architectural science [3].

2 General overview of domestic and foreign research

The overall analysis includes two aspects: annual publication volume and representative journals in the field of architectural science. The annual publication volume is analyzed based on the search results of "all journals" to fully reflect the publication trend; the representative journals are analyzed based on the search results of "important journals" with certain authority to further show the research background and overall pattern.

2.1 Annual publication volume

The number of documents reflects the changes in the degree of attention paid to academic research in this field. Comparing the annual publication volume of Chinese and English documents, different development trends are shown at home and abroad. The publication volume distribution index fitting analysis was performed on 3,049 Chinese documents and 4,068 English documents from 1990 to 2020, and the fitting degree (R^2) of the two curves reached 0.8523 and 0.8382 respectively. It can be considered that the number of Chinese documents on natural ventilation of buildings in this period showed a power-type growth, and the number of English documents showed an exponential growth (Figure 1).

Related research first appeared in 1990, and the overall publication volume was relatively small in the early stage. The number of papers published on naturalventilation of buildings abroad has increased rapidly since 1996, especially from 2010 to 2019. The number of papers published in China has shown great volatility, with 2003 as an important turning point. The outbreak of SARS in that year made people realize the importance of natural ventilation of buildings to health. Before that, there were few related studies, but related studies increased in that year,

and the number of papers published reached its peak in 2016. In recent years, as the SARS craze faded, the number of papers published has declined slightly. As an important factor that directly affects people's health, the outbreak of COVID-19 in 2020 may promote a new growth trend in the number of related papers after 2020.

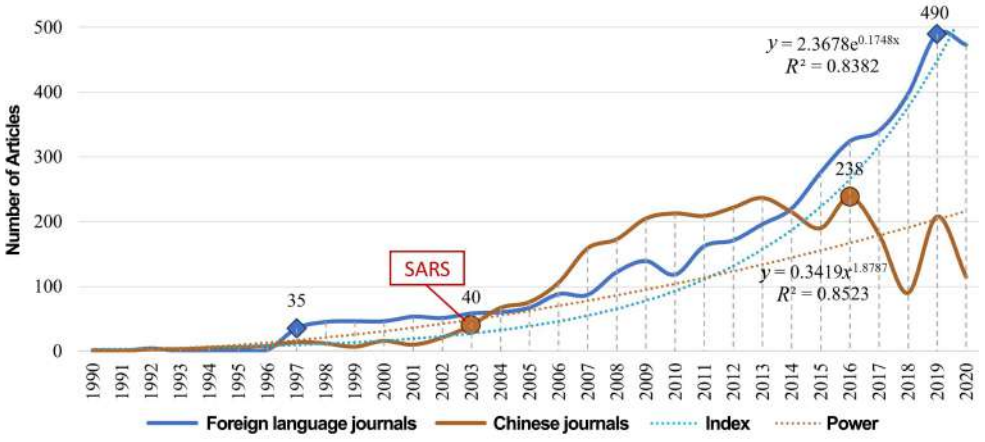

Figure 1 Annual publication of journal papers on naturalventilation of buildings

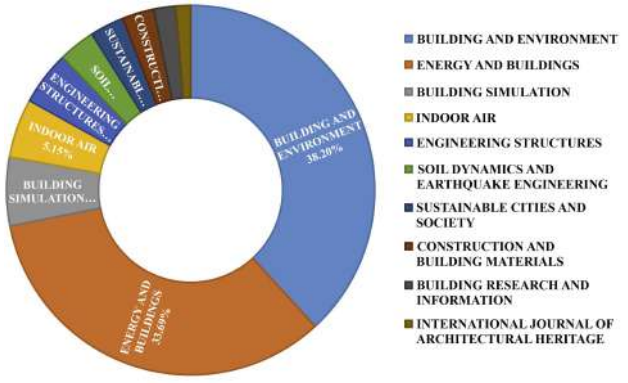

Figure 2 Representative journals of foreign research on natural ventilation of buildings

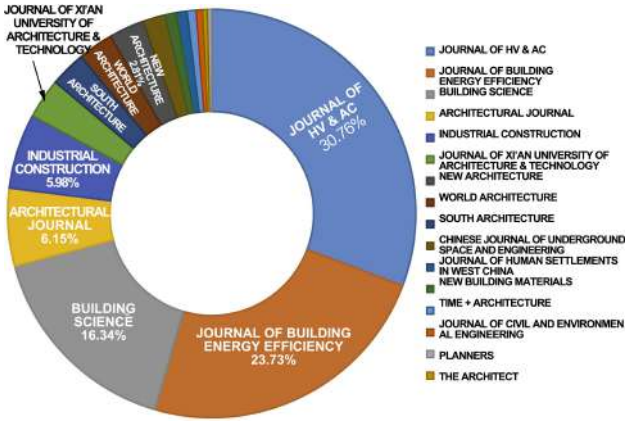

Figure 3 Representative journals of domestic research on natural ventilation of buildings

2.2 Representative journals

The retrieved journals were sorted to obtain a sunburst chart of representative journals on naturalventilation of buildings. In terms of the number of journal articles published, foreign research results on natural ventilation of buildings are mainly published in journals such as Building and Environment, Energy and Building, Building Simulation, and Indoor Air (Figure 2), with 178, 157, 28, and 24 articles respectively, accounting for 83% in total. The impact factors of these four journals are 4.971, 4.867, 2.472, and 4.739, respectively, all of which are heavyweight SCI journals in the field of architecture. Domestic papers are mainly published in journals such as Journal of HV & AC, Journal of Building Energy Efficiency, Building Science, Architectural Journal, and Industrial Construction (Figure 3), with 175, 135, 93, 35, and 34 articles respectively, accounting for 83% in total. The impact factors of these five journals are 0.955, 0.659, 1.093, 1.745, and 0.828, respectively, all of which are important journals in the field of architecture.

3 Research progress at home and abroad

3.1 Research progress abroad

3.1.1 Research hotspots

Using VOSviewer, a co-occurrence analysis of keywords in foreign literature on natural ventilation of buildings (Figure 4) and a statistical analysis of the keywords in the 4,068 foreignarticles retrieved were conducted, dividing the 581 frequently used keywords into five clusters. The higher the frequency of occurrence of the keyword

within the cluster, the larger the sphere in the co-occurrence analysis diagram, which also indicates that the keyword is the hot research topic of the cluster. However, since the same concept is expressed by multiple words (such as energy and energy efficiency in Figure 4, both represent building energy consumption), the size of the sphere cannot well represent the research topic of the cluster, so the merging of similar keywords is particularly important for the hot topic analysis of the cluster. In addition, the connection between keywords in some clusters is weak, not suggesting any theme. Such clusters cannot express the research hotspot in this field, so they can be ignored in the hot spot analysis. Based on this, the research topics can be reclassified into the following four categories: First, air quality and human health, with keywords including health, symptoms, indoor air quality, PM2.5, etc.; second, thermal comfort and building energy consumption, with keywords including thermal comfort, energy, energy efficiency, etc.; third, behavioral management research, with keywords including behavior, management, etc.; fourth, the scope of research methods, with keywords including CFD, large-eddy simulation, turbulence models, wind tunnel experiment, etc.; these four clusters basically represent the main hotspots and methods of foreign research in the field of natural ventilation of buildings in the past 30 years.

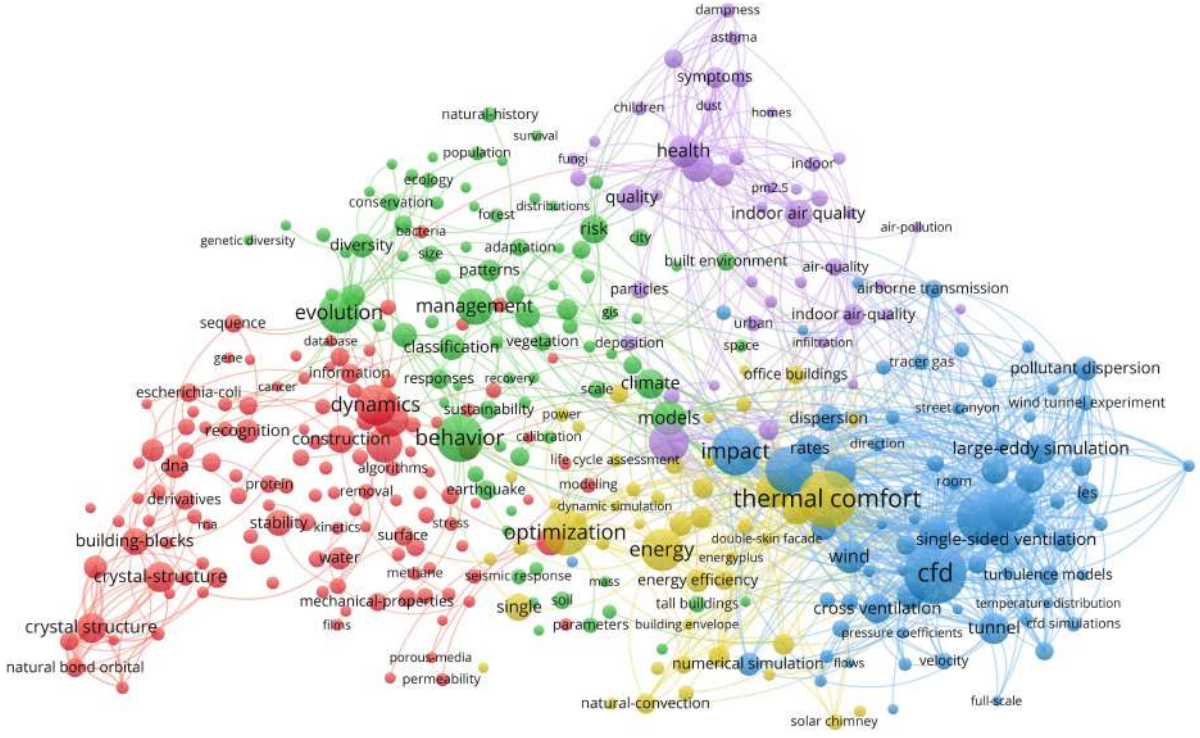

Figure 4 Co-occurrence analysis of keywords in foreign research on natural ventilation of buildings

(1) Air quality and human health

People spend 90% of their time indoors, and indoor air quality (IAQ) plays an important role in people's physical and mental health [8]. Natural ventilation is an important aspect of improving IAQ and reducing sick building syndrome [9]. Opening windows is a necessary condition for achieving natural ventilation, but this will reduce indoor thermal comfort [10]. Therefore, window opening must meet appropriate width and duration to ensure health and thermal comfort requirements. It is worth noting that IAQ will be affected by outdoor pollution due to window opening, so whether a building can be naturally ventilated is closely related to its surrounding microclimate environment. Traffic pollution is one of the important sources of street canyon pollutants. Yang [11] et al. explored the impact of traffic pollutants on the IAQ of buildings near traffic arteries under different window opening ratios, and Tong [12] et al. further explored the impact of different building parameters. In addition to the block scale, atmospheric pollution at the urban regional scale

will also reduce the natural ventilation potential of buildings. Tong [13] estimated the natural ventilation potential of major cities based on China's atmospheric environmental quality and found that the natural ventilation potential in the north in winter is smaller than that in the south. Therefore, how to improve the outdoor environmental quality in the north and thus improve the natural ventilation potential of buildings is a topic worthy of attention.

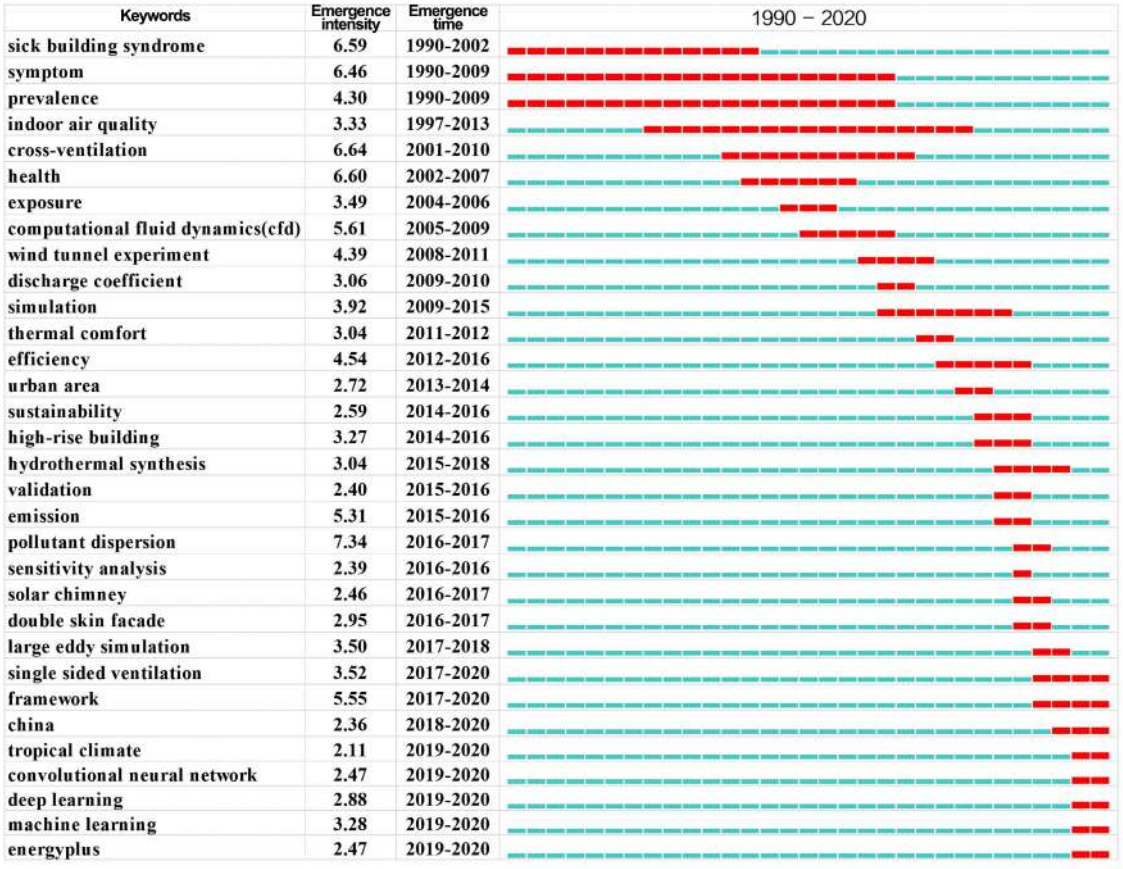

Figure 5 Burst detection of foreign research on natural ventilation of buildings

(2) Thermal comfort and building energy consumption

People's satisfaction with the indoor thermal environment is usually called thermal comfort, which is an important aspect of evaluating building performance. C. Andido [14] and Kwong[15] found that high wind speed can increase the thermal comfort range. Naturally ventilated buildings have a wider thermal comfort range due to their higher wind speed [16]. Generally, it is more difficult for single-sided ventilated buildings to obtain good natural ventilation conditions, resulting in poor indoor thermal comfort. Scholars have done a lot of research on this. Montazeri [17], D. Cui [18] and S. Omrani [19] found that the balcony of a single-sided ventilated building has a significant improvement on the thermal comfort of its attached space. While pursuing comfort, people inevitably use mechanical equipment, which increases energy consumption of the building. Therefore, research on thermal comfort and building energy consumption is carried out simultaneously. From the perspective of energy saving, natural ventilation is an ideal way, as it can achieve energy saving by cooling down the indoor space [20, 21], but its instability makes it difficult to meet the thermal comfort needs the whole time. Therefore, natural ventilation needs to be combined with HVAC. With the development of building equipment automation, the technology of controlling natural ventilation by using automatic window opening and closing systems has been widely studied [22, 23], the integration of which into mixed ventilation can save a lot of energy [24]. In future research, more attention will be paid to the role of intelligent control in reducing building energy consumption and

better promoting the sustainable development of buildings.

(3) Behavior management

Natural ventilation is closely related to human behavior. Therefore, the research on natural ventilation is inseparable from human behavior. The research on human behavior is mainly reflected in two aspects. The first is the impact of human behavior on building energy consumption [25]. Sorgato [26] and Cedeno [27] found that human window opening behavior has a significant effect on reducing building energy consumption. The second is the prediction and control of human window opening behavior. Zhang [28] et al. explored the method of predicting window opening and fan use in naturally ventilated buildings. Schulze [29] et al. tried to develop the most energy-saving window opening behavior control plan for naturally ventilated buildings while ensuring air quality and thermal comfort. It can be seen that human behavior is not only related to building performance, but also that the consideration of human behavior can mitigate the inaccuracy of natural ventilation performance prediction in the current design stage. Mining human environmental control behavior preferences through big data is a good research topic.

3.1.2 Research Trends

Burst detection is used to characterize the phenomenon of keyword transition in a short period of time, which helps to grasp the research hotspots in a certain field at different stages. Through CiteSpace, a keyword burst analysis of 4,068 English articles was conducted to obtain the research development trend of foreign countries (Figure 5). Foreign research on natural ventilation of buildings mainly includes four stages: (1) 1990-2004, the research focused on air quality and human health, and keywords such as sick building syndrome, prevalence, indoor air quality, and exposure appeared frequently; (2) 2005-2010, the research method was the focus of attention, and the newly emerging keywords included CFD (computational fluid dynamics), wind tunnel experiment, simulation, etc. (3) 2011-2015, the newly emerging keywords were relatively broad, mainly thermal comfort, efficiency, sustainable development, etc., and the research content mainly focused on building thermal comfort and building energy saving. (4) 2016-2020, the newly emerging keywords focused on pollutant dispersion and research methods. Keywords such as pollutant dispersion, large eddy simulation and deep/machine learning appeared frequently.

In general, the research on natural ventilation of buildings abroad shows two trends. First, the research content tends to be diversified, from the early focus on air quality and human health to the later focus on thermal comfort, energy saving, sustainable development, etc. Although the research on indoor air quality has not diminished, the research perspective has shifted from the mechanism of air quality's impact on human health to the diffusion pattern of pollutants. Researchers began to explore the impact of the surrounding environment of buildings on the cross-household transmission of pollutants [30] and the transmission pattern of pollutants in various indoor spaces [31, 32]. Secondly, more attention is paid to the introduction of new methods. In the latest published papers, interdisciplinary research is a prominent feature. For example, quantitative methods such as sensitivity analysis [33] are used to measure the correlation between architectural morphological elements and building environmental performance; computer artificial intelligence and numerical simulation platforms are introduced in the architectural design stage, and the natural ventilation performance is automatically generated in reverse based on computer artificial intelligence algorithms.

3.2 Domestic research progress

3.2.1 Research hotspots

Using the same method to conduct keyword co-occurrence analysis on domestic research on natural ventilation of buildings (Figure 6), the research hotspots of nearly 30 years can be reclassified into the following four categories: First, building energy conservation, with keywords including building energy conservation, energy-saving design, building energy consumption, etc.; second, thermal environment, with keywords including thermal environment, thermal comfort, indoor thermal environment, etc.; third, green building, with keywords including green building, building design, ecological building, low-energy building, etc.; fourth, the scope of research methods, with keywords including numerical simulation, CFD, computational fluid dynamics, etc.; these four clusters basically represent the main re-

search hotspots and methods of domestic building natural ventilation research in the past 30 years.

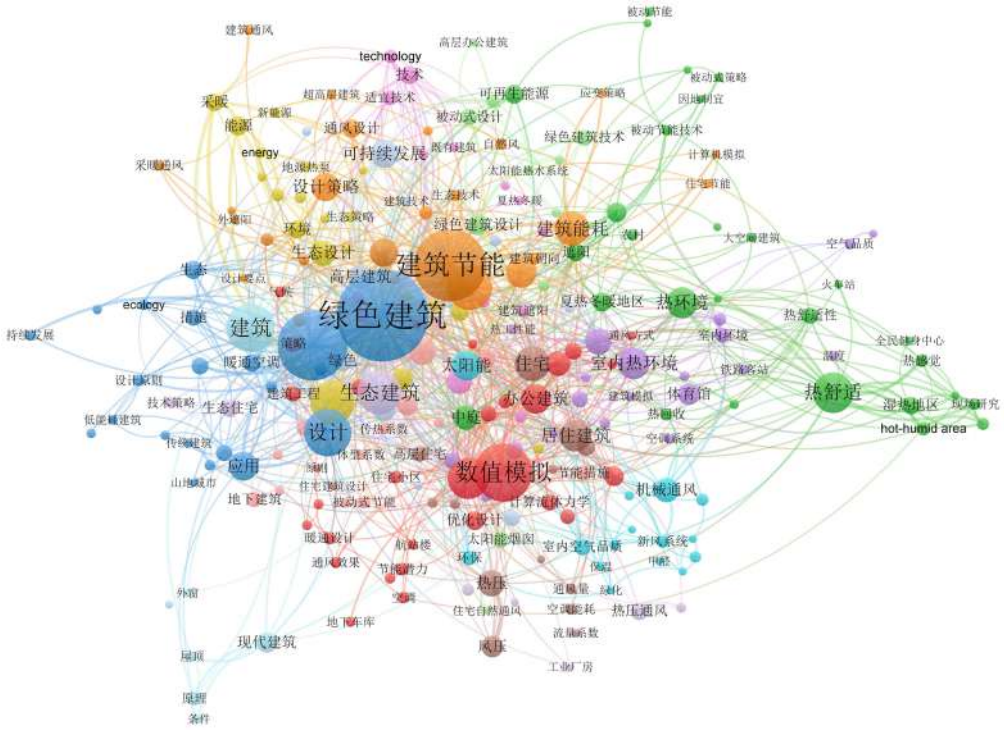

Figure 6　Co-occurrence analysis of keywords in domestic building natural ventilation research

Keywords	Emergence intensity	Emergence time	1990 – 2020
Wind pressure and heat pressure	4.94	2006-2010	
Indoor air quality	3.90	2006-2008	
Heat pressure	3.20	2006-2007	
Ecological building	3.27	2006-2008	
Solar energy	2.94	2006-2007	
Sustainable development	4.35	2007-2008	
Layout	3.11	2007-2009	
Residence	6.84	2008-2009	
Principle	3.01	2009-2011	
Shading	4.21	2009-2011	
Ecological strategy	3.20	2009-2011	
Underground building	2.79	2009-2011	
Indoor thermal environment	4.25	2009-2010	
Renewable energy	2.10	2009-2011	
Green building design	2.82	2010-2016	
Environmental protection	2.10	2010-2011	
Energy-saving technology	2.96	2011-2013	
Green energy saving	3.40	2013-2020	
Solar chimney	3.28	2013-2018	
Optimal design	2.81	2013-2020	
Computational fluid dynamics	2.72	2014-2016	
Areas hot in summer and warm in winter	3.21	2014-2020	
Application	3.50	2014-2018	
Simulation	4.48	2014-2018	
Office building	2.65	2014-2020	
Airflow organization	3.14	2014-2017	
Residential building	2.54	2015-2018	
Architectural design	3.20	2015-2017	
Natural ventilation	8.42	2018-2018	
Numerical simulation	3.74	2018-2020	
Gymnasium	4.08	2018-2020	
Ventilation frequency	3.44	2018-2020	

Figure 7　Burst detection analysis of keywords in domestic building natural ventilation research

(1) Building energy conservation

Natural ventilation can significantly reduce the use of air conditioning and reduce building energy consumption [35]48-49. That the focus of domestic research on natural ventilation of buildings is building energy conservation is mainly reflected in two aspects. The first is the energy-saving effect of natural ventilation. Studies have shown that natural ventilation can reduce the mechanical ventilation time of gymnasiums by about 84.7% [36], and it also has a significant energy-saving effect on bedrooms in residential buildings, especially south-facing bedrooms [37]. The second is the prediction of natural ventilation potential by energy-saving analysis. Since natural ventilation is an important means to reduce energy consumption, energy-saving analysis has also become an important method for evaluating the potential of natural ventilation [38]. Huang He et al. [39] developed the annual hourly simulation software DeST-Vent + for natural ventilation and building energy consumption. By simulating the annual air-conditioning energy consumption of buildings under different natural ventilation conditions, the energy-saving potential of different natural ventilation forms was analyzed. Research on building energy conservation has always been popular. In the context of our country becoming one of the countries with the highest energy consumption in the world, research on natural ventilation energy conservation is still worthy of attention in the future.

(2) Thermal comfort

Thermal comfort research mainly includes the evaluation of thermal comfort performance under natural ventilation conditions and the study of the impact of natural ventilation on thermal comfort. Thermal comfort performance research is usually carried out in the form of field surveys, and the research covers different cities [40], different seasons [41], and different populations [42]. It covers a wide range of building types, among which public buildings are the most common, residential buildings account for a large proportion, and other types of buildings are relatively few [43]. The research on the impact of natural ventilation on thermal comfort is mainly reflected in the two aspects of climate adaptability and building thermal performance. Yan Haiyan et al. [44] compared the impact of dry hot and humid hot climates on human thermal response. The results showed that under natural ventilation conditions, climate can change people's adaptability to the environment. Wind speed has different effects on improving people's thermal comfort under different climate conditions. Wind speed is more effective in humid and hot areas. Wang Xianling [45] 173-175 analyzed the impact of blinds parameters on indoor thermal comfort under the coupling of shading and natural ventilation. Yuan Liting et al. [46] revealed the influence of heat transfer coefficients of exterior walls and exterior windows on indoor thermal comfort of naturally ventilated buildings. When the window-to-wall ratio is less than 0.6, strengthening the insulation of exterior walls can more effectively improve indoor thermal comfort. When the window-to-wall area ratio is greater than 0.6, strengthening the insulation of exterior windows is more effective.

(3) Green buildings

The"green" in green buildings means that the building makes full use of passive technology to provide people with healthy, applicable and efficient use space. Green buildings include land saving, energy saving, material saving, water saving, and environmental protection. Energy saving is an important aspect of green building evaluation and has always been the focus of green building natural ventilation research. It also involves the regulatory effect of natural ventilation on the indoor environment [47] 170-171. At present, the natural ventilation research of green buildings is mainly focused on public buildings, including gymnasiums [47], transportation buildings [48], office buildings [49], etc. Related research is gradually using quantitative methods to study how to optimize building form, window opening, etc., to provide guidance for green building design. For example, using CFD to simulate the natural ventilation environment avoids the uncertainty of qualitative analysis, and also helps compare different building plans to select the best one [50].

3.2.2 Research trends

The development trend of building natural ventilation research was obtained byburst detection analysis of 3,049 Chinese documents through Citespace (Figure 7). Before 2006, domestic building natural ventilation research was in

its initial stage, and no emerging keywords appeared; it then went through three development stages: (1) 2006-2009, the research content mainly focused on the principles of natural ventilation and ecological sustainability; (2) 2010-2013, the research theme is green building and energy saving; (3) 2013-2020, the emerging research focuses on CFD numerical simulation and indoor environment.

In general, the research in the field of natural ventilation of buildings in China shows two trends. First, the research goal has shifted from building energy saving to improving indoor environmental quality. "Green building" has been the focus of many scholars in the past 10 years. As an important aspect of green building, building energy saving has always attracted much attention in the research of building natural ventilation. Keywords such as "green building design, building energy-saving design, green energy saving" have emerged in the past 10 years (Figure 7). With the country issuing the "Healthy China 2030" Planning Outline in 2016, healthy buildings have received attention. And the research focus of building natural ventilation has shifted to improving indoor environmental quality. As a result, keywords such as "airflow organization, air change frequency" have emerged (Figure 7). Studies have shown that natural ventilation fares better at creating a good indoor environment than mechanical ventilation [51, 52], so using natural ventilation to improve the indoor environment is the focus of future research. Secondly, the research objects are more diverse, and keywords such as "office buildings, residential buildings, and gymnasiums" have emerged. Further review of relevant literature shows that the research on natural ventilation of residential buildings focuses on the impact of windows [53], patios [54], balconies [55], building orientation and floor plan [35] 47-48 on ventilation effects, while those targeting office buildings focus on the improvement of ventilation effects by curtain wall ventilators [56], atriums and side courtyards [57], and those targeting large-space buildings mainly focus on vents [58, 59], building forms [60, 61], etc. Different from the previous research on the principles of natural ventilation and energy conservation, the later period pays more attention to improving people's quality of life through architectural design.

4 Comparison of domestic and foreign research

4.1 Comparison of research basis and research content

From the perspective of research basis, foreign research in the field of building natural ventilation has an absolute advantage, and the development is relatively mature, showing an overall exponential growth. In contrast, the research on natural ventilationof buildings in China is still in the early stages of development. The number of papers published only began to show an upward trend after the SARS in 2003 and has slightly declined in recent years with the fading of the SARS craze, showing a lack of sustained research (Figure 1). Affected by national policies and economic development, the number of articles is generally small, and the quality of the journals where they appear needs to be further improved.

From the perspective of research content and research trends, foreign academic circles focus on indoor air quality and human health in the field of building natural ventilation. Its development process has undergone a relatively obvious transformation: the research content has shifted fromthe mechanism of the impact of air quality on human health in the early days to the diffusion of pollutants under natural ventilation (Figure 8). However, the research content in the field of natural ventilation of buildings in our country is relatively extensive, with diverse hotspots. For a period of time, it focused on green building and building energy consumption. In recent years, it has begun to explore the improvement of indoor air quality based on numerical simulation technology (Figure 8). The regulating effect of natural ventilation on indoor air quality depends largely on the outdoor environment. The environmental pollution caused by heating in winter in northern cities in our country leads to limited natural ventilation potential of buildings. Therefore, it is of great significance to study the improvement effect of natural ventilation on indoor environmental quality based on the coupling of indoor and outdoor environments in our country.

The consideration of human behavior has always been a hot topic in the study of natural ventilation of buildings abroad, but domestic research has not paid much attention to human behavior. The natural ventilation of buildings directly affects indoor comfort, which in turn af-

fects the artificial control of indoor environment. In addition to environmental performance, human behavior is also affected by psychological factors such as privacy. The current building performance simulation platform oversimplifies the human behaviorprocess and cannot faithfully reflect the complexity of controlling environment artificially, which affects the accuracy of simulation prediction and makes it difficult to achieve the expected effect of architectural design after the building is put into use. In future research, we should make full use of data mining to collect information such as preferences and specific needs of artificially controlled environments and realize the exploration of differentiated needs of building users. Combining statistical data and questionnaire survey data, the optimization design of natural ventilation of buildings supported by multi-source data will become a trend in future domestic research.

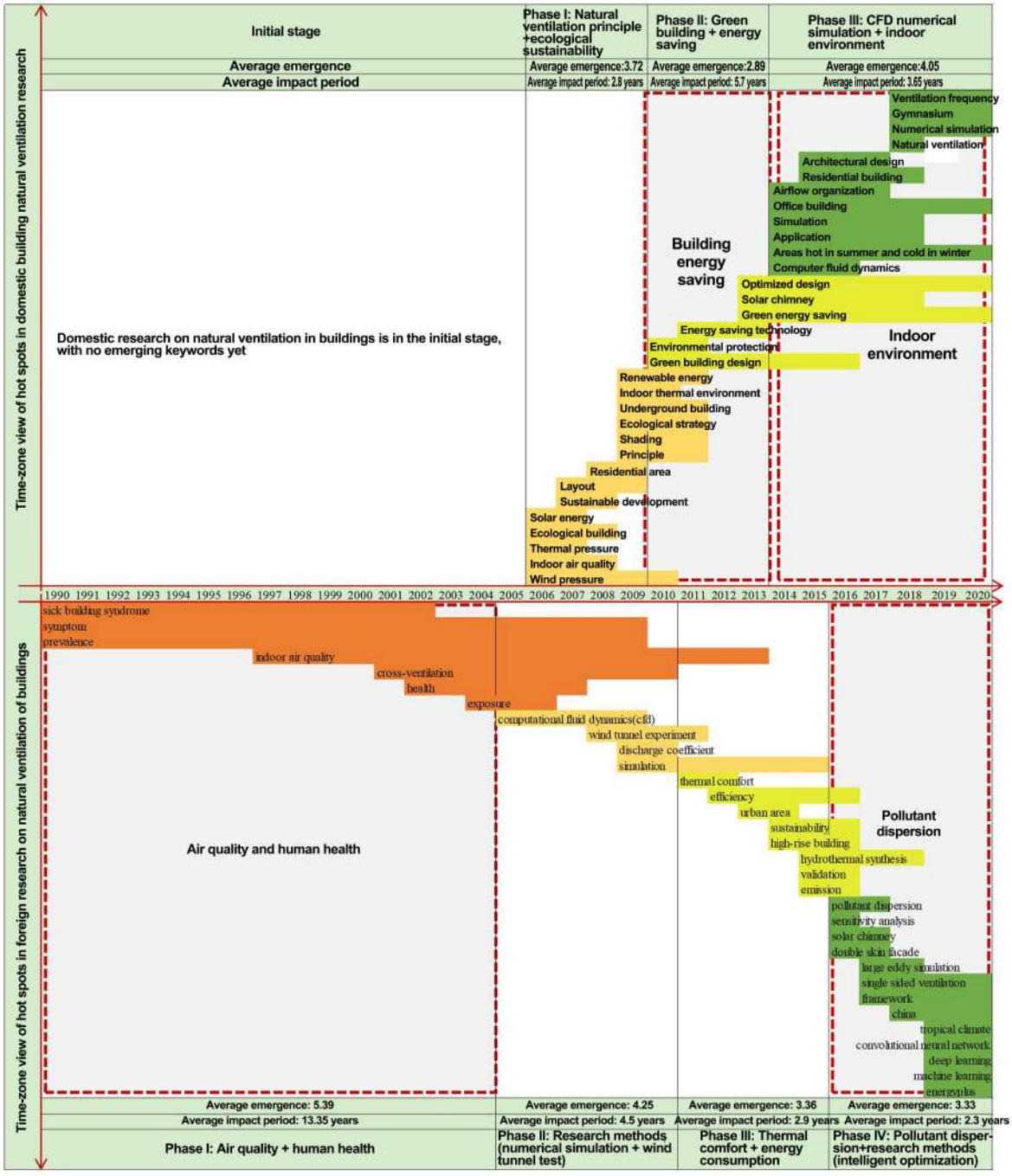

Figure 8 Time-zone view of hot spots in domestic and foreign research on natural ventilation of building natural ventilation

4.2 Comparison of research methods

From the perspective of research methods, foreign scholars have explored more research methods than domestic scholars. In theburst detection analysis of CiteSpace, a total of eight keywords related to research methods emerged in foreign countries, while only three were found in China. Whether it is experimental or numerical simulation methods, the relevant keywords emerged earlier in foreign countries than in China. Domestic research on research methods is still in its infancy. In the past two years, foreign countries have paid more attention to the introduction of new methods, and the exploration of research methods has turned interdisciplinary. Scholars have tried to introduce computer artificial intelligence and numerical simulation platform coupling in the architectural design stage, relying on computer artificial intelligence algorithms to automatically generate design plans. Compared with foreign countries, there are fewer studies in this area in China, and no relevant keywords have emerged in the burst detection analysis (Figure 9).

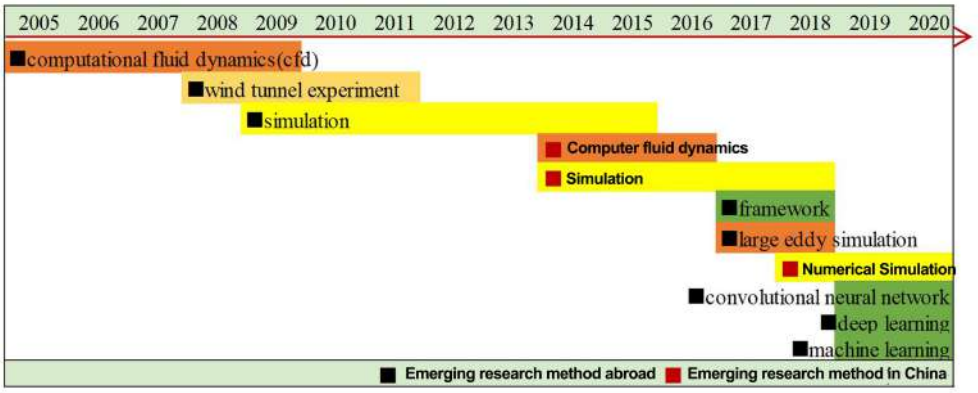

Figure 9 Time-zone view of methods in domestic and foreign research on natural ventilation of buildings

Traditional natural ventilation research methods include two categories: experiments and numerical simulations. Experiments include actual measurements and wind tunnel tests. Wind tunnel tests first appeared in foreign countries, and their results are usually compared with numerical simulation results to verify the validity of numerical simulation results [62]. Compared with numerical simulation, field measurement and wind tunnel testing are costly and time-consuming, and it is difficult to study different schemes at the same time. Therefore, there has not been much development in recent years. However, numerical simulation methods have the advantages of being fast, simple, accurate, effective, and low-cost, and are favored by researchers. At the same time, with the development of computer technology, the cycle and economic cost of numerical simulation have also been greatly reduced, and it has become a popular research method for studying natural ventilation at home and abroad in recent years.

Commonly used models for numerical simulation mainly include computational fluid dynamics model (CFD), multi-zone network model (multi-zone), and coupling model. Among them, CFD model has the highest accuracy, followed by coupling model, and multi-zone is the worst [63] (Table 1). CFD model is mainly used to predict indoor air flow and temperature distribution in the preliminary design stage, such as establishing a model to analyze the ventilation conditions of buildings with different orientations or geometric shapes and studying the influence of many influencing factors such as orientation, shape [64]59-62 and opening geometric parameters [65]18-22 on natural ventilation performance. The commonly used software for this model includes ANSYS Fluent [65]18, PHOENICS [64]58, Fluent Airpak [66], etc. The CFD model is the most used numerical simulation method in the field of building natural ventilation in the past 10 years, and its usage rate far exceeds that of the other two models. Foreign scholars are still enthusiastic about CFD models, while in China, the popularity has slightly declined in the past two or three years (Figure 10). The multi-zone network model started earlier in the United States, the United Kingdom and other countries, and has developed to a relatively mature stage. It is mainly used to

compare indoor environmental quality under different natural ventilation conditions [67]. CONTAM and COMIS are the most popular multi-zone models in natural ventilation research [68]. The coupling model is a new method developed in recent years to combine the advantages of the CFD model and the multi-zone network model. It is mainly used to explore the impact of traffic pollution on the indoor environment of street-facing buildings [69]. Foreign scholars use multi-zone models and coupling models much more frequently than domestic scholars. Relatively speaking, domestic scholars are more willing to use CFD models to study the natural ventilation of buildings (Figure 10).

Table 1 Brief list of research methods in the field of building natural ventilation

Simulation model	Principle	Accuracy	Advantages	Disadvantages
CFD model	A microscopic approach which uses conservation equations such as mass and energy to analyze the building velocity field, temperature field, and pollutant concentration field	* * *	Detailed description of the characteristics of indoor parameters	The amount of calculation is large, the calculation time is long, and therequirements for computers are high.
Multi-zone network model	A microscopic approach which uses conservation equations such as mass and energy to analyze the air flow, pressure distribution, and pollutantdispersion of the entire building	*	Fast calculation speed and short time, can be used for long-term dynamic simulation and air infiltration problems [70]	It is impossible to study the flow field, and the results are relatively rough
Coupling model	Dividing the space into CFD zones and multi-zone zones, using the multi-zone results as the boundaries of the CFD zone for CFD simulation, and then feeding the results back to the multi-zone for calculations in the remaining areas	* *	Higher accuracy than multi-zone model, shorter calculation time than CFD model	The simulation process is complex.

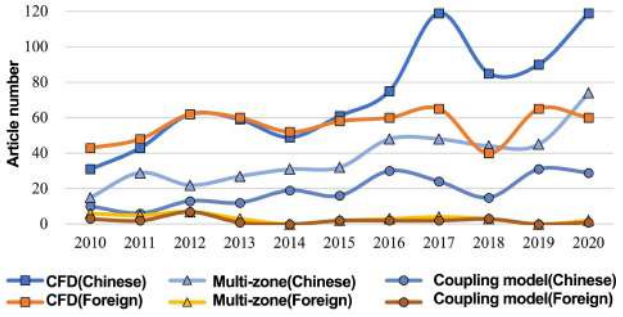

Figure 10 Comparison of numerical simulation methods in important journal articles at home and abroad in the past decade

Intelligent optimizationis a new method introduced in the field of natural ventilation in recent years. It appeared earlier in foreign countries, and there have been many related studies in recent years, with obvious keyword emergence (Figure 9). However, the development of intelligent optimization in China started later, and no keywords have emerged yet. Intelligent optimization can be divided into three types according to their different technical characteristics: "optimization based on CFD numerical simulation [71]", "optimization based on wind tunnel tests [72]" and "optimization based on proxy models [73]102-104". The CFD-based optimization method refers to the iterative optimization of coupling CFD and optimization algorithms at the scheme stage. However, since CFD simulation calculations are time-consuming, researchers have proposed optimization methods based on wind tunnel tests and proxy models to address this shortcoming. Existing studies have elaborated and compared the principles, technical characteristics, advantages and disadvantages of these three optimization methods in detail [73]100-104. The basic process of optimization is as follows: first, variables are selected as the optimization target; then, technical model tests were conducted to explore the influence of various influencing factors on the objective function; finally, the results obtained were evaluated to find excellent genes and form excellent schemes (Figure 11). This reverse generative optimization method based on building performance has become an important method for optimizing building performance design today and plays an important role in the optimization design at the scheme stage.

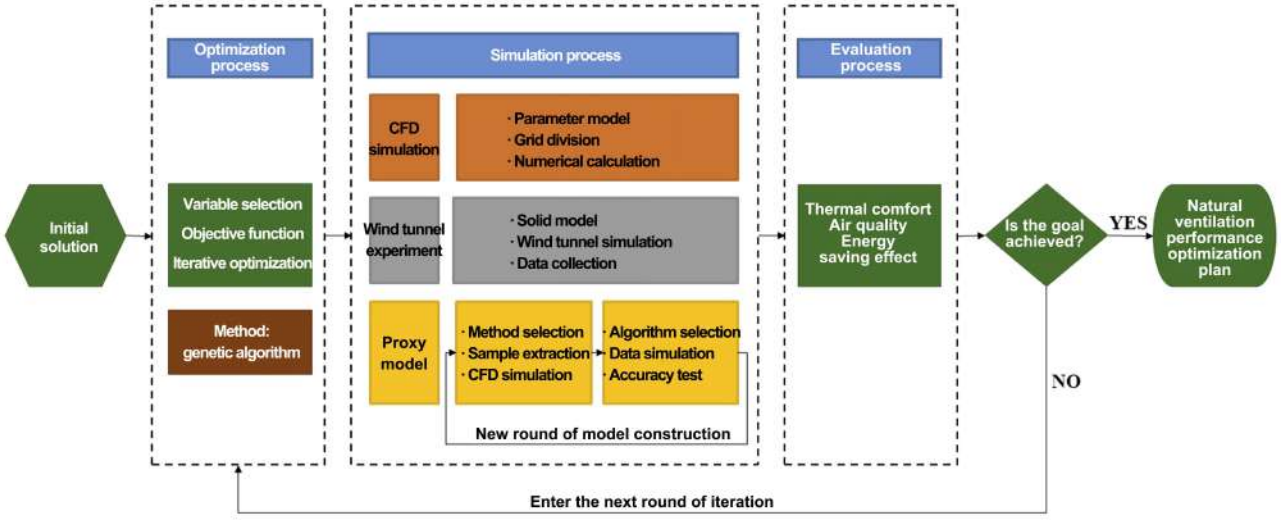

Figure 11 Optimization process for natural ventilation performance

Summary and discussion

By means of bibliometric and visual analysis of the research on natural ventilation of buildings at home and abroad from 1990 to 2020, the current status of research is summarized from the number ofarticles and journal distribution. Based on this, a comprehensive analysis of research hotspots and research trends is conducted. In summary, the characteristics of the current research on natural ventilation of buildings at home and abroad and the issues that need attention can be found:

Compared withother countries, the research on natural ventilation of buildings in China is still in the early stages of development, and there is still a lack of sustained research. In addition, a large number of domestic studies are still at the stage of energy-saving analysis and energy-saving design strategies for green buildings. As far as natural ventilation itself is concerned, there is little discussion on the issues of air quality and health under natural ventilation of buildings. In addition, the research process lacks consideration of user behavior, which will reduce the accuracy of the results in the prediction stage.

Combining practical understanding of the research field and the analysis of the diagrams, it can be seen that future research and practice can make innovative contributions in the following aspects:

(1) Explore strategies to improve indoor environmental quality under indoor and outdoor coupling. The microclimate environment around the building directly affects the wind field around the building and the ventilation capacity of the building. Therefore, it is necessary to fully consider the impact of the microclimate environment around the building on the natural ventilation of the building and conduct on-site measurements based on actual weather conditions to explore the impact of the outdoor microclimate environment on the indoor environmental quality.

(2) Conduct window opening behavior research based on new methods and technologies. Natural ventilation affects the frequency of artificial controls of environment by changing the indoor comfort level. At the same time, human behavior is also affected by psychological factors such as privacy. In future research, we should focus on analyzing and integrating complex user behaviors and explore the preferences and specific needs of artificially controlled environments in different regions and types through new methods and technologies, so as to explore the differentiated needs of building users.

(3) Pay attention to improving the health performance of buildings. The 2020 COVID-19 epidemic has pushed health concerns to a new level. As an emergency“shelter” during public safety incidents, whether buildings have “anti-epidemic” functions is the focus of future architectural design. Therefore, the relationship between the building form and the risk of cross-infection between indoor and outdoor air of buildings under natural ventilation will become a top priority in future research in the field of ar-

chitectural science.

Figure and table sources

Allfigures and tables are created by the authors.

Notes

1) In 2016, the CPC Central Committee and the State Council officially issued the Outline of the"Healthy China 2030" Plan, which put forward the vision and goals of China's health and medical development in the next 15 years.

2) In 2015, the Chinese government proposed the goal of "China will achieve carbon emissions peak around 2030 and strive to achieve it as soon as possible" at the Paris Climate Change Conference.

3) Important journals refer to high-quality scientific and technological journals in the field of architectural science (T1-T3 level) published by theArchitectural Society of China in 2020.

4) Accuracy: The numerical simulation results of different models are compared and verified with wind tunnel tests. The closer the simulation is to the actual measurement, the higher the accuracy. Among them, CFD simulation uses the large eddy simulation method.

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Application of Machine Learning in Architectural Design-a Review

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ABSTRACT: This paper first clarifies the two popular concepts of "machine learning" and "neural network," combs the current cutting-edge research in the field of architectural design, then introduces the interface tools needed from the perspective of architectural design practice, and looks forward to the trend of application in the future.

KEY WORDS: machine learning; neural network; architectural design; cutting-edge research

Currently, neural network deep learning technology is widely used in fields such as image recognition and recommendation algorithms, and related concepts like machine learning, neural networks, and artificial intelligence are becoming increasingly well-known to the public [1]. What are the specific applications of machine learning and neural network technology in the field of architecture? How do these cutting-edge technologies intervene in the architectural design process? These have become issues of concern to many architectural scholars.

The concepts of machine learning and neural networks are relatedbut have different focuses, which have led to confusion and misunderstandings. Most architects still cannot grasp the essence of neural networks and machine learning. This paper uses knowledge graphs to sort out the current international research status in architecture and related fields, analyzes the potential and limitations of using such tools in architectural design, and sorts out the cutting-edge research results of machine learning for architects and architectural design stages, exploring its potential to intervene in future architectural design processes.

1 Concept and classification of machine learning and neural networks

1.1 Concept and classification of machine learning

Machine learning is an interdisciplinary subject involving probability theory, statistics, convex analysis and other disciplines. It acquires new knowledge from data, improves its own performance based on this knowledge "experience" to make effective decisions in new situations, and simulates human learning behavior to a certain extent. Since the early 1950s, two schools of thought have emerged: "symbolism" based on logical representation and "connectionism" based on neural networks. The "statistical learning" idea represented by support

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vector machines (SVM) and kernel methods, which appeared in the 1990s, provides effective algorithmic tools for contemporary machine learning applications [2]. For different machine learning tasks, algorithm engineers use different "machine learning algorithms" - such as support vector machine (SVM) algorithm, k-nearest neighbor (KNN) algorithm, decision tree algorithm, etc.for classifying labeled data[1]; LASSO algorithm for regression prediction of labeled data; K-means algorithm for clustering analysis of unlabeled data, principal component analysis (PCA) algorithm for dimensionality reduction analysis of high-dimensional data that explores intrinsic correlation, etc. [3] (Figure 1).

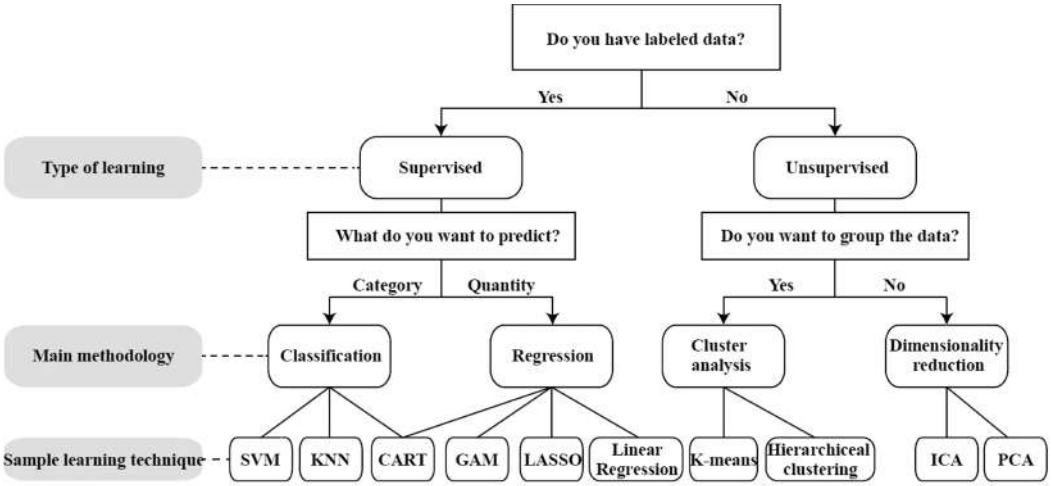

Figure 1 Types of machine learning and corresponding representative algorithms

1.2 Concept of neural network

Neural network in the field of machine learning refers to "neural network learning," which describes the core design idea of a class of tools to achieve the aforementioned machine learning tasks - building a neuron model inspired by biological neural networks to achieve machine learning tasks [2]. A neural network is a widely parallel interconnected network composed of simple adaptive units. Its organization can simulate the interactive response of biological nervous systems to real-world objects [4].

The most basic component of a neural network is a neuron. The signals transmitted by other neurons are transmitted to a certain neuron through weighted connections. The total input of these signals is processed by the activation function and then transmitted to other neurons. Many such neurons are connected according to a certain structure to form different types of neural networks. Generally, the use of neural networks is divided into two stages: training and prediction - in the training stage, known data is input, and the weight value of each neuron is updated through the back propagation algorithm. In the prediction stage, the data to be predicted is input, and the classification, regression, clustering and other prediction results of the new data are calculated using the neural network model after the weight value is updated (Figure 2) [2]. However, theconnectionist nature of neural network determines that its internal computing mechanism cannot be clearly explained, making it a "black box" tool.

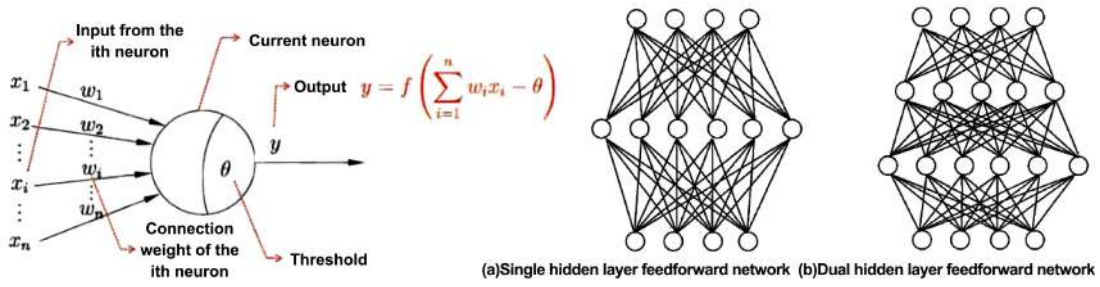

Figure 2 Schematic diagram of the basic principle of feedforward neural network

2 Research based on literature analysis

CiteSpace is a tool for literature analysis based on the principle of knowledge graph. By analyzing the citation relationship characteristics and keyword frequency of different documents, it can explore the research hotspots and research trends in a certain discipline [5]. In a broad sense, architectural engineering design includes architectural design, building structure, HVAC system, construction management and other fields. As "architecture," architectural design-related research is more exploratory and applied because it is more practical. At present, in the field of architectural engineering, the mainstream research of machine learning focuses on air conditioning and energy consumption, building structure, and construction engineering management, as it is suitable for data prediction and feature analysis tasks in complex multivariate scenarios.

The Scopus database was used to analyze the literature of cutting-edge international academic conferences in the field of architectural design, and a total of 123 research documents from 1999 to 2019 were obtained. Since the number of citations of international conference papers is very small compared to journal papers, it is impossible to conduct effective literature co-citation analysis. The keyword analysis function in CiteSpace is used to explore the potential application hotspots of machine learning in the field of architectural design. Noun keywords form a word cloud,where the size of the keyword indicates the number of times it appear and the distribution of keywords reflects the concentration of research hotspots, as shown in the following figure (Figure 3).

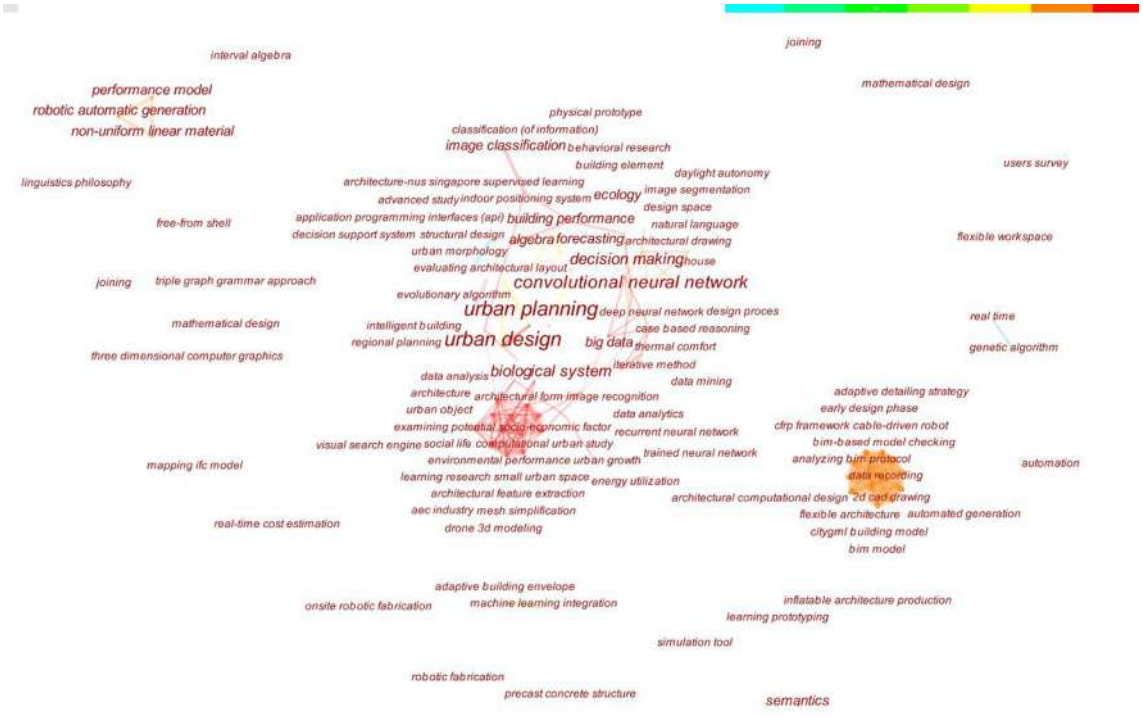

Figure 3 Potential application hotspots of machine learning in architectural design

The following conclusions can be drawn from the visualization results:

(1) Urban design/urban planning related issues are mentioned frequently, and related keywords form a certain degree of concentration, with diversified research directions, including environmental performance, architectural feature extraction, social life, etc.

(2) Keywords such as building performance/performance model, robotic automatic generation, image classification, decision making, and no-uniform linear material have a high frequency of occurrence, representing the current hot research directions.

(3) Therange of other keywords is quite wide, and the distribution is relatively even, including architectural layout, free-form shell, BIM-based model check, evolutionary algorithm, data mining, real-time cost estimation, and many other different research directions, which represent the current academic exploration and practice in various

subdivided research directions.

It is worth noting that, since machine learning is still an emerging technology, its application in the field of architectural design is still in its infancy, and the number of related studies is not large. Since keyword analysis of a small number of documents cannot guarantee a clear and accurate research context, this article will obtain a more in-depth research status through manual screening of the latest international conference papers.

3 Research on cutting-edge applications of machine learning for architectural design

In order to solve the lag of Scopus and other databases in collecting cutting-edge literature from international conferences, the latest research literature in the field of architecture was manually retrieved (including important international conferences and related journal papers in the past three years as of June 2020) to show the cutting-edge application of machine learning technology in fields related to architectural design. According to the algorithm architecture and research field focus, all the literature can be divided into 12 major algorithm categories andeight research directions. All the above literature is presented in a table as shown in the following table (Table 1).

According to the complexity of the machine learning algorithm, all the machine learning algorithms involved are divided into non-deep learning algorithms and deep learning algorithms. In addition to the traditionalsimple artificial neural network (ANN) algorithm, non-deep learning algorithms also include regression analysis, SVM, SOM algorithm, etc., which are widely used in other construction engineering fields besides architectural design. Deep learning algorithms involve multiple layers of complex neural networks, including the more popular CNN, GAN, RNN algorithms and style transfer algorithms, graph-based algorithms, reinforcement learning algorithms, etc. Deep learning algorithms have better recognition capabilities for high-dimensional data and abstract features.

3.1 Analysis of cutting-edge applications from the perspective of algorithms

The application of traditional non-deep learning algorithms (excluding Simple ANN shallow neural networks) is concentrated in research areas such asarchitectural form, building performance and user behavior. Although these machine learning algorithms have been maturely applied in engineering fields such as structure and HVAC, they have not been widely mentioned in cutting-edge research in the field of architectural design. Among them, the SOM self-organizing neural network maps high-dimensional data to a two-dimensional grid and performs self-organizing clustering. It can be used to refine building forms [15] [16], judge the correlation between a large number of morphological control parameters of complex structures and the final construction results [21], analyze the complex correlation between environmental factors and various physiological indicators of users [17] (Figure 4), and can also be creatively applied to CFD fitting calculations of building wind environment [18], showing great potential for future applications. Nathan Brown et al. applied the PCA principal component analysis method to the optimization process of large-span truss structures, integrating the height parameters of the truss control points and abstracting them into several control variables with different weights that affect the performance of the truss structure, ensuring that architects can have further room for free form adjustment while intuitively grasping the performance of the building structure [7] (Figure 5). It is worth noting that all applications above involve research related to building performance to coordinate complex nonlinear parameter relationships.

Machine learning algorithms represented by Simple ANN learn the corresponding input-output association patterns from multivariate high-dimensional data sets, thereby establishing an input-output association model. By inputting new data into the trained prediction model, the corresponding data output can be predicted. This property is widely used in the field of building energy consumption prediction to accelerate the speed of building energy consumptionoptimization and is called the "surrogate model" or "metamodel" method (surrogate model/metamodel) [80] [81] [30] [31] [32] (Figure 6). Similarly, the metamodel method can be used in the direction of structural performance optimization, such as assisting designers in judging the performance trend of the entire scheme search space

Table 1 Literature review on cutting-edge applications of machine learning for architectural design

		Feature recognition	Plane topology generation and optimization	Robotic arm construction process	Urban form	Architectural form	Structural optimization	User behavior analysis	Building performance
Non-deep learning	Traditional regression algorithm								[6]
	PCA analysis					[7] [8]			
	SVM								[9]
	KNN/K-means	[10]			[11]	[12] [13]		[14]	
	SOM					[15] [16]		[17]	[18]
	Simple ANN			[19] [20] [21]	[22]	[23] [8] [24] [25]	[26] [27] [28]	[29]	[30] [31] [32] [33] [34] [35]
Deep learning	CNN	[36] [37] [38] [39] [40] [41] [42] [43]		[44]	[45] [46]	[47] [48]		[14]	[49]
	GAN	[50] [51] [52]	[53] [54] [55]	[56] [57]	[58]	[59] [60]			[61] [62]
	RNN		[63]	[64] [65]				[66] [67]	
	Style transfer				[68]	[69] [70] [71] [72] [73] [74]			
	Machine learning algorithm based on graph structures		[75] [76] [77] [63]						
	Reinforcement learning				[78]		[79]		

during the optimization process [26], accelerating structural static optimization calculations [27], and quickly predicting structural performance involving more material property settings [28]. Compared with the aforementioned machine learning algorithms, simple ANN can more effectively capture the inherent correlation of complex parameter constraints and have a wider range of applications. It can fit the morphological changes of architectural forms as

the control points move [23], proving its ability to effectively capture nonlinear complex parameter relationships for interpolation calculations, which can also be applied to the optimization of robot arm operation paths [19][20]. Wang Zhenyu et al. used the surrounding urban environment data of 440 built museums in China (the number and location of bus stops, surrounding road grades, etc.) and the location of the main entrance of the museum as input and output to train a single hidden layer neural network. The neural network can decide the best entrance location of the museum based on the new given museum site selection environment, and the consistency rate is 70%-90% compared with manual selection [22]. Christian Theoborg [8] (Figure 7) and Zheng Hao [24] used morphological parameters as the input of the neural network and the observer's score of morphological beauty as the output of the neural network, thereby "mimicking" people's subjective preferences to assist the process of architectural form optimization. The above two types of applications can be regarded as fitting the human decision-making process, which is a relatively basic form of "artificial intelligence."

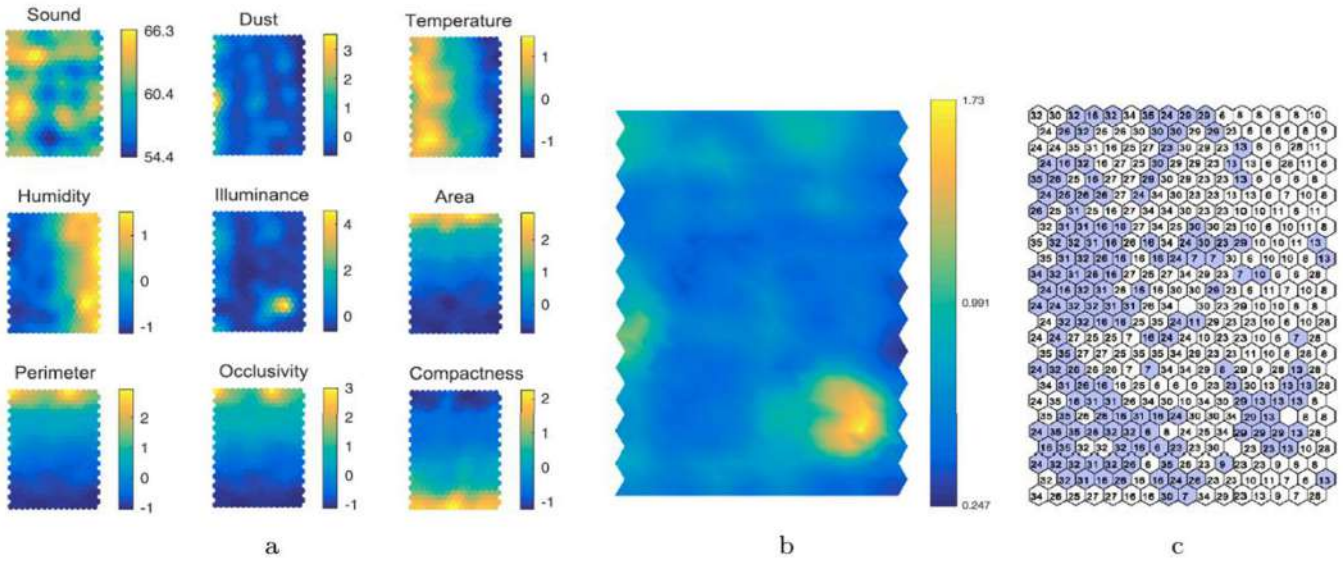

Figure 4 Using SOM neural network to explore the correlation between different environmental data and human physiological response indicators

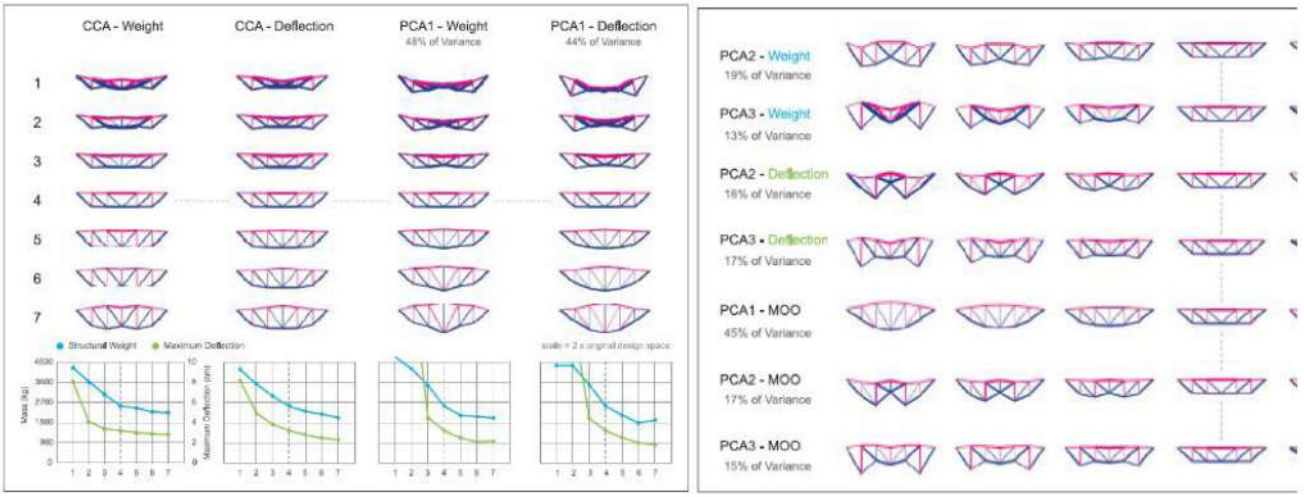

Figure 5 Effects of different weights obtained by principal component analysis (PCA) and canonical correlation analysis (CCA) algorithms on truss shape and performance

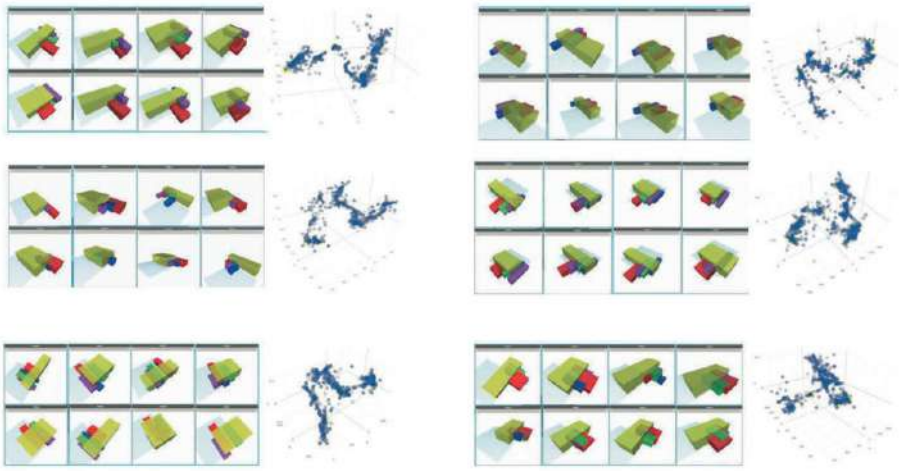

Figure 6 Machine learning-based "surrogate model"/"meta-model" approach to assist building performance optimization

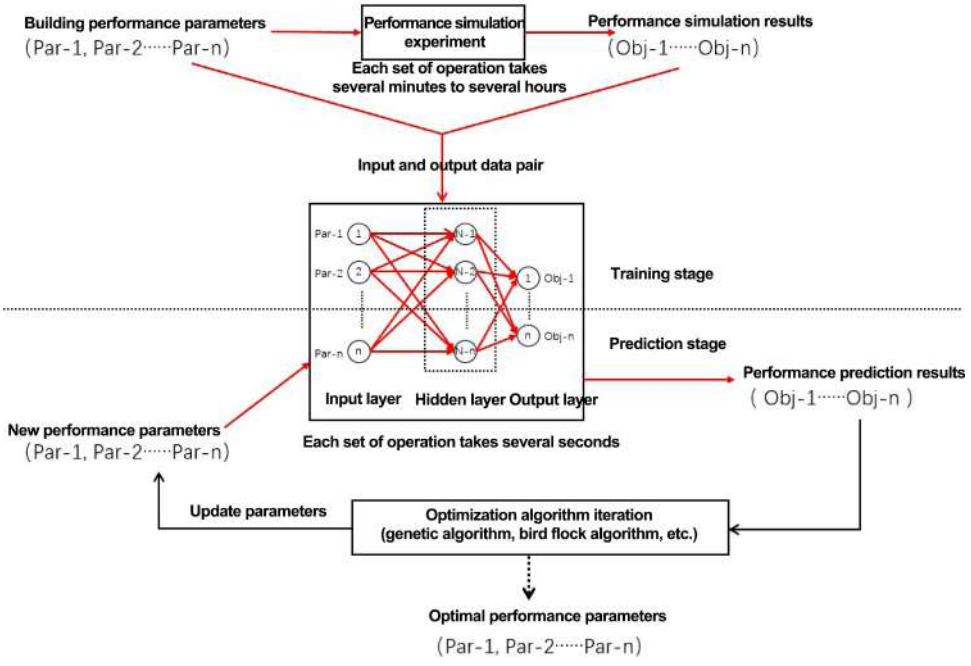

Figure 7 Neural network simulation of architects' preference of forms and PCA cluster analysis results

Convolutional neural network (CNN) has become an important tool in the field of image feature recognition due to its ability to interpret abstract features of two-dimensional images. Yuji Yoshimuraet al. input images of works by architects of different styles into a deep convolutional neural network for training, resulting in a CNN that can identify abstract architectural style features from the newly input architectural images, infer which architect the style of the building belongs to, and mark which areas of the architectural image the inference is based on in the form of a pseudo-color image [36] (Figure 8). This is the most intuitive application of two-dimensional image recognition technology in the field of architectural design. Furthermore, a recommendation system called DANIEL can extract the building layout logic based on the input building plan, and output several building plans with similar features, providing buyers with a variety of candidate options [43] (Figure 9). In addition to performing traditional image recognition and classification tasks [36][37][38][39][40][41][42][44] to assist the architectural design process, CNNs can also automatically identify urban block types at the city scale with the help of satellite images [45], expanding the application of CNNs to the field of urban morphology planning.

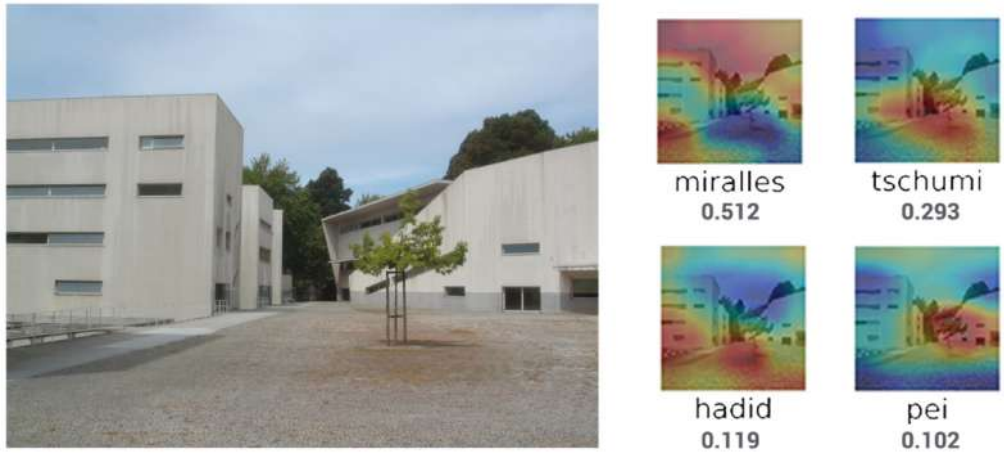

Figure 8 Deep learning neural network recognizing architectural style

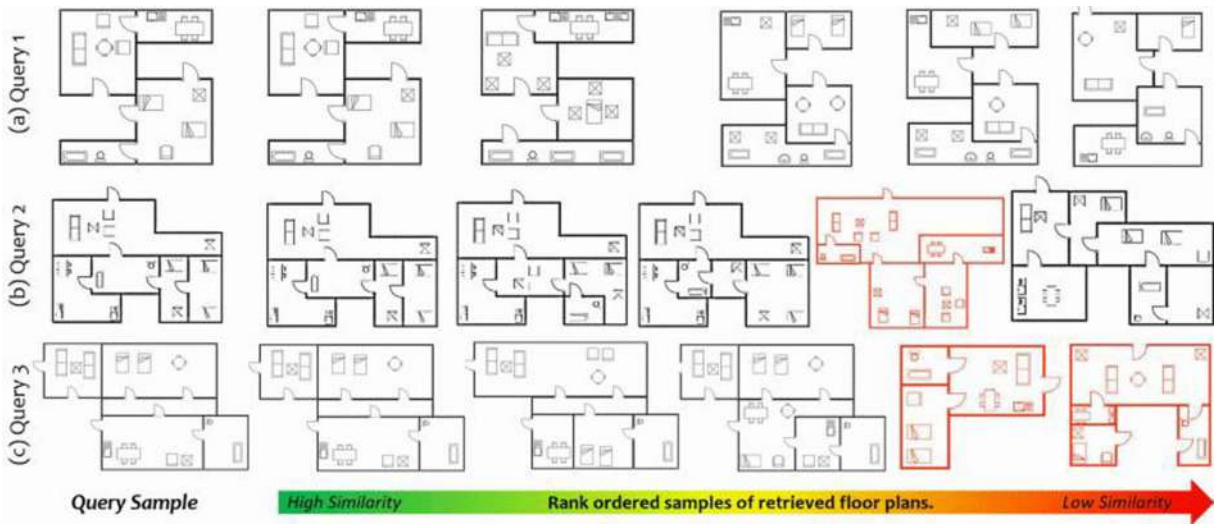

Figure 9 Deep learning neural network recommendation system generating similar candidate solutions based on reference plane

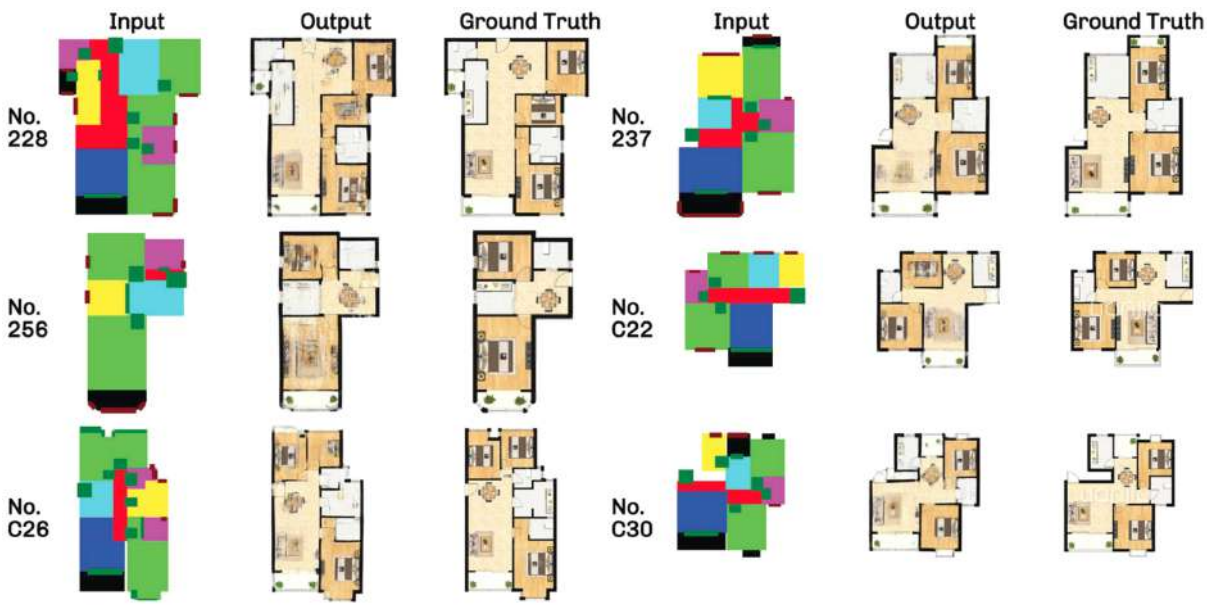

Figure 10 Deep learning neural network generating architectural plan based on functional color block map

The input and output parameters ofa generative adversarial network (GAN) are both two-dimensional image data. Zheng Hao, Huang Weixin et al. obtained 155 residential floor plans from the lianjia.com website and drew corresponding functional color block diagrams to mark room functions with different colors, which were connected to the pix2pixHD neural network [82] as the output and input ends for training. The trained neural network can generate realistic floor plans based on the newly input functional color block diagram [53] (Figure 10), which proves the feasibility of using the architectural floor plan as a two-dimensional image for information exchange. Stanislas Chaillou made a further attempt at plane generation on this basis, using the GAN to simulate the entire floor plan design process of building red line-building base outline-room division-door and window opening design-furniture arrangement. A large number of alternative options can be generated for each step. Relying on the real-time tree selection interface, designers can flexibly filter the generated results of each step [55] (Figure 11). On the other hand, the research using scene photos as a medium also shows the potential value GANs: the domestic Xiaoku team launched the "Rosetta Project" in 2017, using the styleGAN neural network to conduct in-depth learning of a large number of existing excellent architectural design cases, establish a huge knowledge base on design style, logic and concepts, and output the learned intelligent design results for designers to refer to [59] (Figure 12). The GAN Loci study by Steinfeld et al. compared the potential of Pix2pixHD and styleGAN neural networks to reproduce the "Genius Loci" of different cities, demonstrating the powerful recognition and induction ability of GAN neural networks for abstract features [58] (Figure 13).

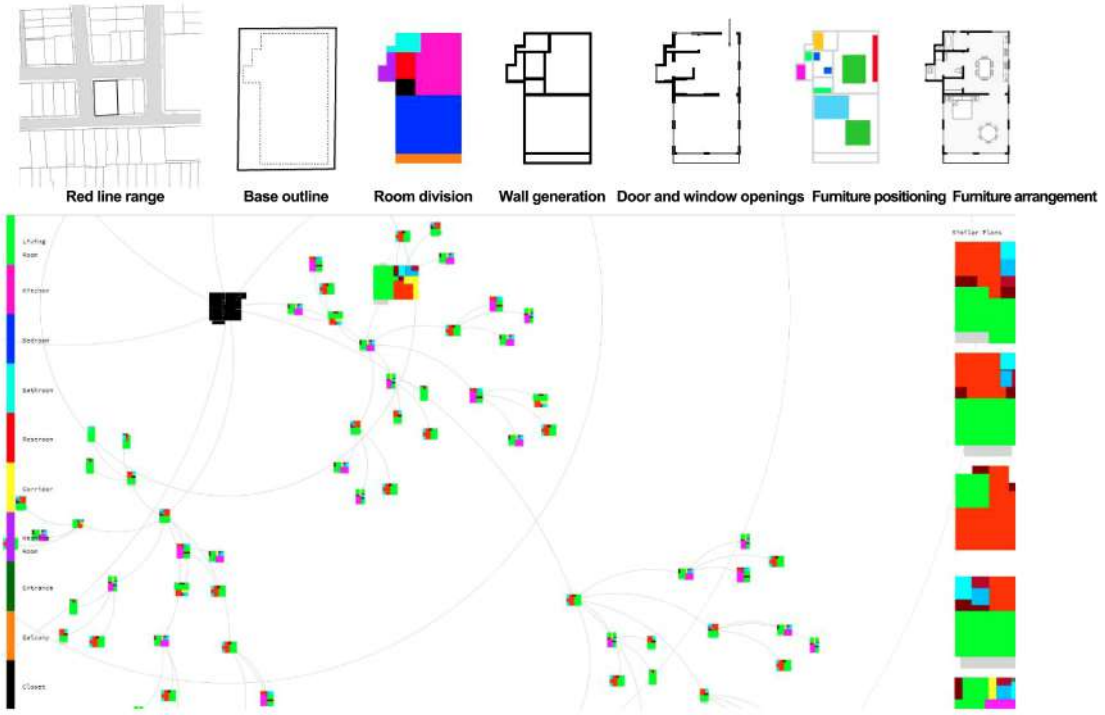

Figure 11 Architectural plan design process and tree-like scheme screening interface based on generative adversarial network (GAN)

Compared with CNN, recurrent neural network (RNN) can flexibly process data sequences of different lengths, so it is used in fields such as text and speech semantic analysis. This allows it to not only simulate crowd behavior based on time seriesdata [66], but also identify the topological similarity of architectural planes [63] and predict the deformation characteristics of inhomogeneous materials in combination with graph structure [2]. Furthermore, if the architectural design steps are regarded as time series data to train RNN neural networks, it can understand the nonlinear design decision process and assist architects in making decisions [67].

Style transfer technology for two-dimensional images, graph structures used for social data processing, and reinforcement learning algorithms have found their place in research directions such as assisting designers in obtaining creativeinspiration [68][69][70][71][72][73], identifying architectural space topological relationships [75][76][77], generative design based on dynamic feedback [78] and structural optimization methods [79]. Among them, Professor Sun Cheng's team applied style transfer technology to three-dimensional architectural forms to assist in the style consideration of three-dimensional architectural forms based on the semantic information of two-dimensional conceptual intention maps, which provided new ideas for future architectural design [74].

Figure 12 Modern style building facade based on styleGAN

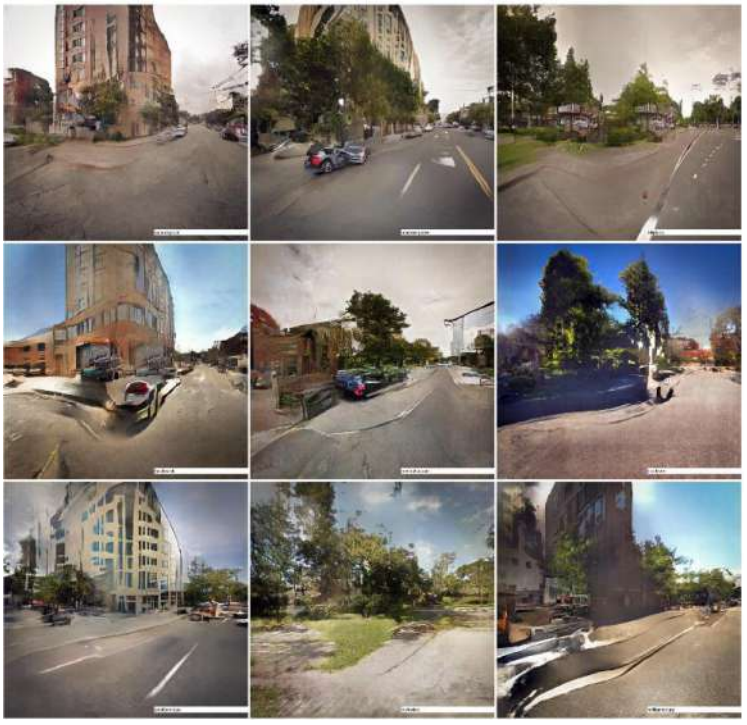

Figure 13 Cityscape image generation based on pix2pixHD

3.2 Analysis of cutting-edge applications based on different research directions

Feature recognition technology has received widespread attention with the recent popularity of CNNs. Feature recognition methods based on CNNs mainly rely on two-dimensional images and are used in different branches of architectural design to help designers improve efficiency. Yuri Kato et al. combined CNN with Google Maps to extract street interface color matching patterns [38] to provide a basis for subsequent architectural and urban planning decisions; KIM, JINSUNG et al. studied how machine learning can help computers automatically identify the types of unknown building components [37].

The application of machine learning at the urban morphology level is also mainly based on pixel processing of urban planning images, and then using algorithms such as CNN,

GAN, and Style Transfer to identify abstract features and convert morphological styles based onthem. Peng Qian et al. from Tongji University discussed the current application prospects of artificial intelligence in the field of urban planning and used CNN to perform large-scale and detailed discrimination of urban texture and land use classification [45] (Figure 14).

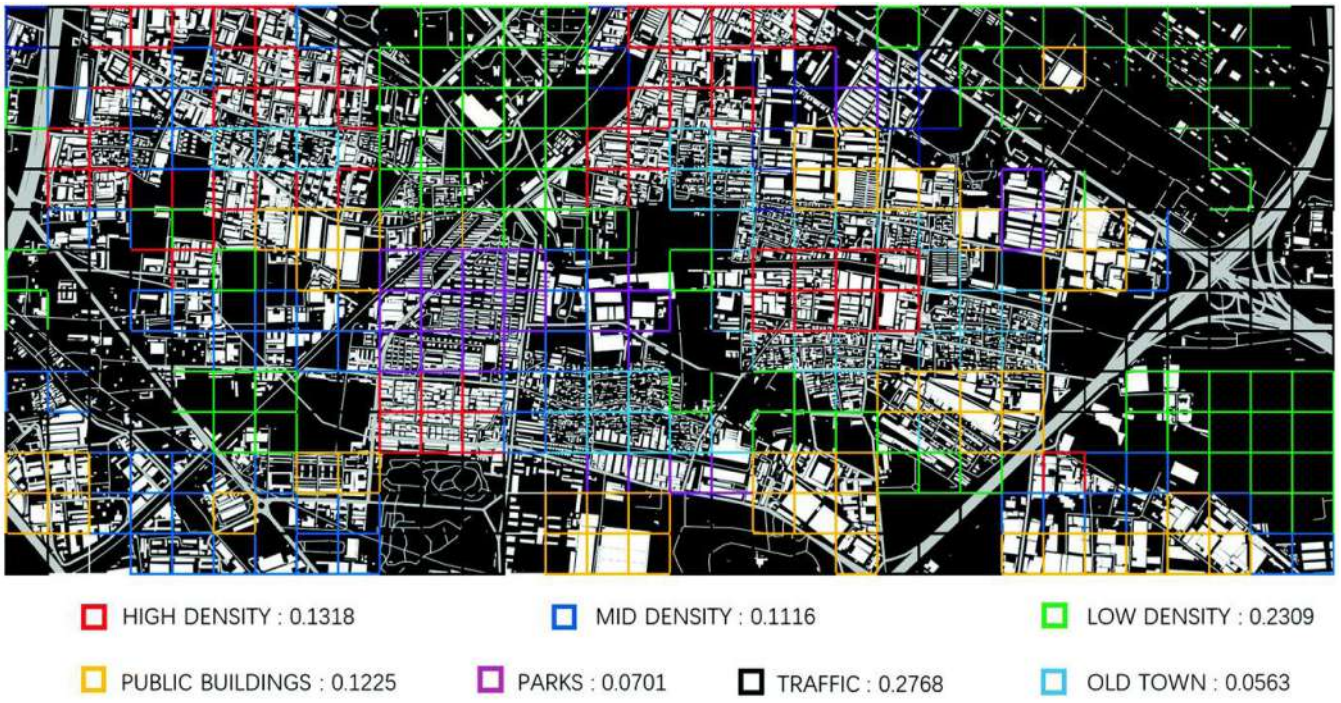

Figure 14 Urban morphology recognition based on CNN neural network

The study of architectural plan and spatial topology hasthe development of two completely different paths. The first is the generative design method based on the GAN network mentioned above. It uses the pixel format image of the architectural plan for training to obtain new plan layout schemes. However, this plan generation method cannot exchange data directly and accurately with vector modeling software. The second machine learning method based on graph structure can more effectively express the topological relationship of architectural space and has greater potential to be integrated into the traditional architectural design process [63][75][76][77] (Figure 15, Figure 16).

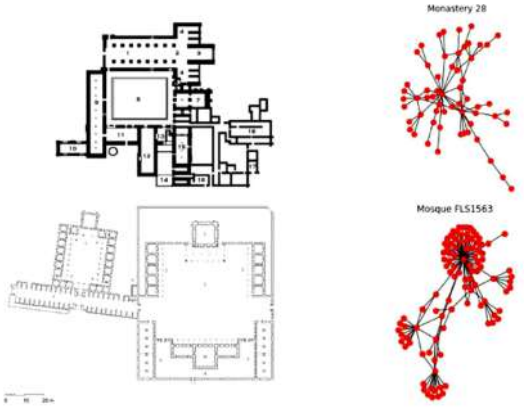

Figure 15 Topological analysis of architectural plan

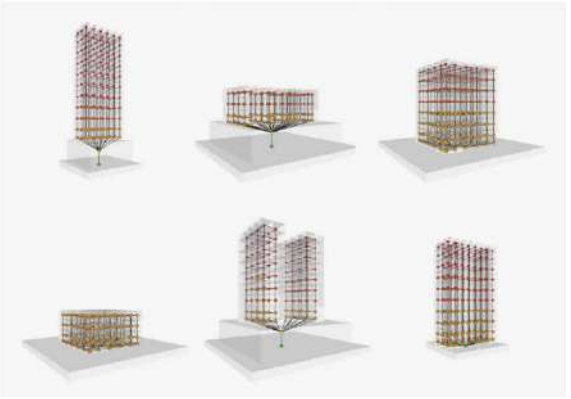

Figure 16 Visualization of spatial organization diagram structure of three-dimensional building

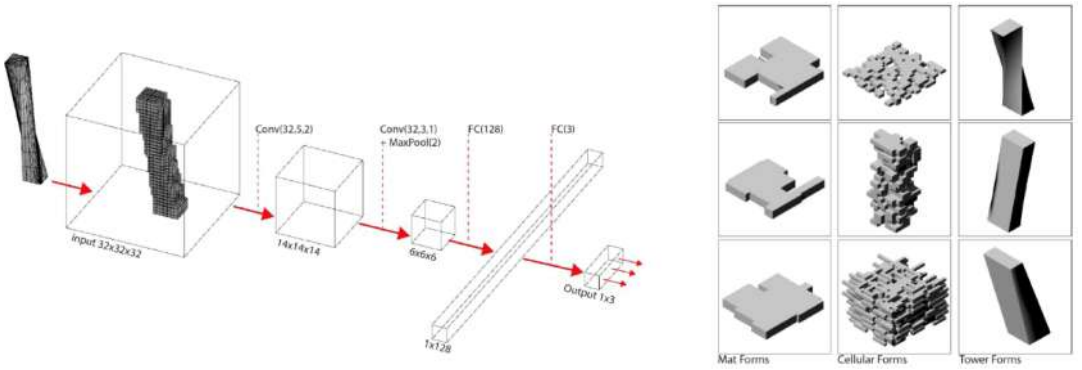

Figure 17 Architectural form translation based on pixelation

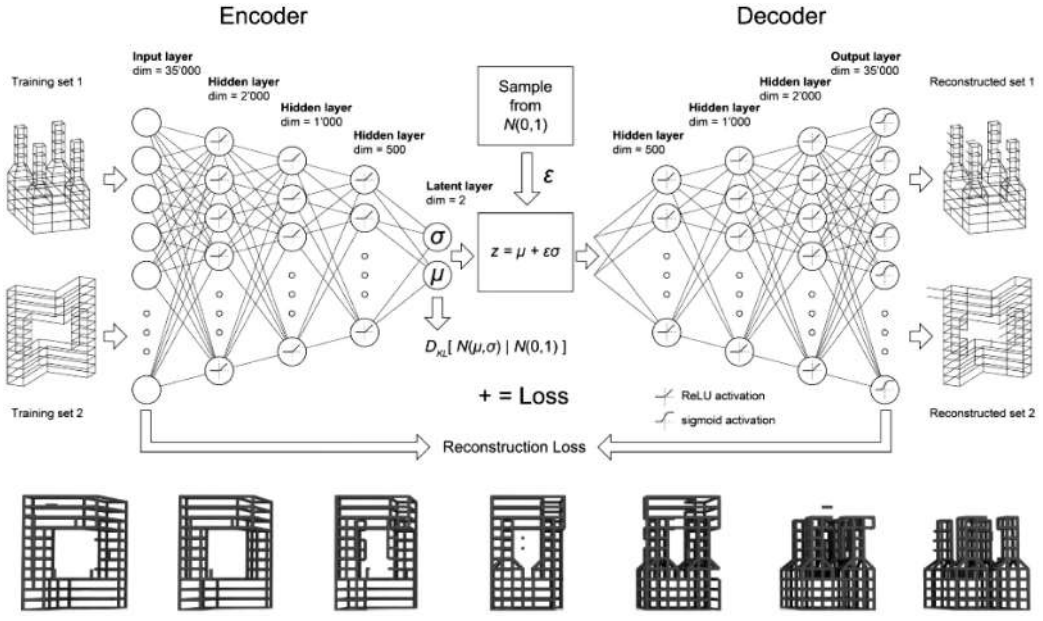

Figure 18 Method of mixing architectural form features based on autoencoder network

At the architectural form level, in addition to extracting the intrinsic correlation between form control parameters and subjective evaluation parameters, another research direction with potential value is how to translate three-dimensional architectural form information for use by machine learning algorithms. By pixelating the three-dimensional form of the building and treating it as three-dimensionally distributed pixel points, a corresponding three-dimensional convolutional neural network (3dCNN) can be created. David Newton established a 3dCNN network by linking the Keras neural network tool on the grasshopper platform, which can currently identify three characteristics of buildings [47] (Figure 17). Jaime de Miguel et al. added neighboring information around each sampled "pixel point" on this basis. The translated architectural form information was input into the autoencoder network and compressed into a vector in a latent space through four hidden layers. By training two different architectural forms, smooth sampling between two corresponding vectors in the latent space can yield a mixed result of the characteristics of the two architectural forms [25] (Figure 18), which is similar to the results of architectural form research based on the SOM algorithm [16] (Figure 19). Steinfeld et al. established an application framework of machine learning in generative design by taking another path to translate the three-dimensional form of buildings: the images of the cut surfaces of the three-dimensional building entities in different directions were used as the input of the neural network to describe the form information, and the GAN neural network was further used to generate new three-dimensional entities, proving the feasibility of this form translation method [60] (Figure 20).

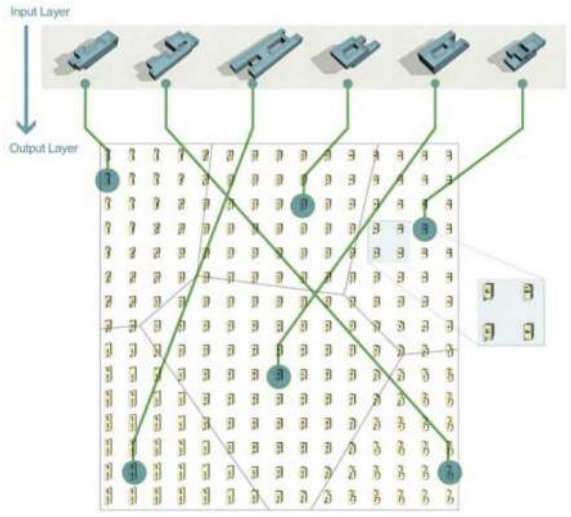

Figure 19 Method of mixing architectural form features based on SOM network

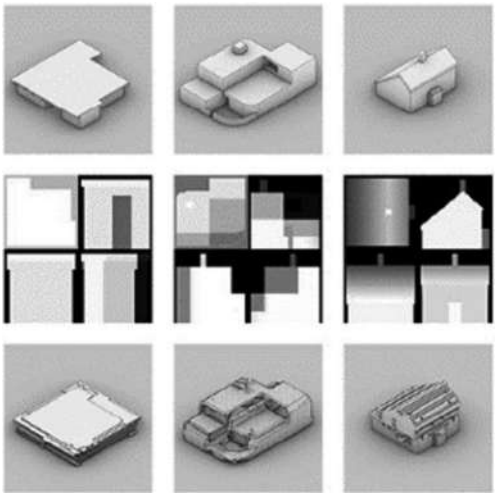

Figure 20 Architectural form translation based on multiple views

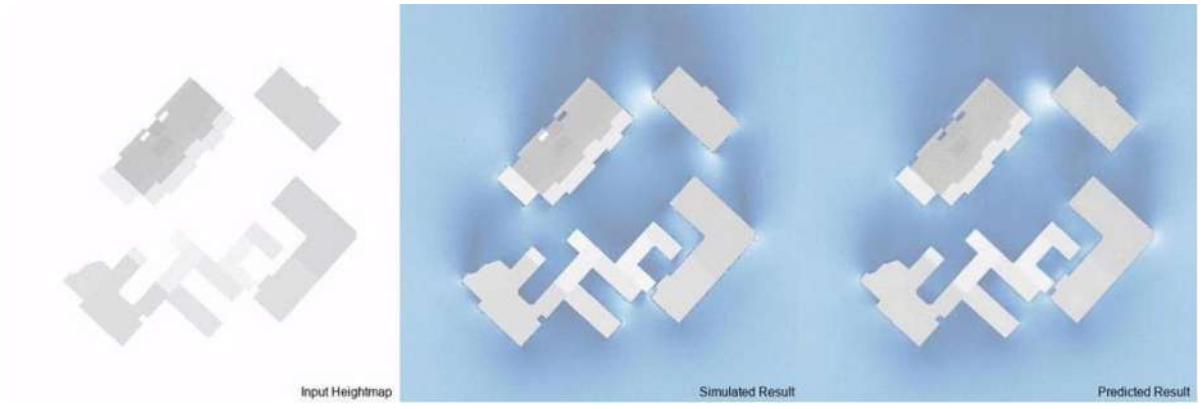

Figure 21 Comparative analysis of real-time building wind environment prediction based on urban elevation grayscale image and traditional simulation results

Machine learning as a pattern recognition tool has shown its potential in the fields of robotic arm construction, structural optimization, user behavior analysis, and building performance analysis and optimization. Among them, Angelos Chroniset al. used GAN neural networks to establish a real-time modeling visualization platform based on Rhinoceros3D, focusing on solving the environmental performance simulation at the urban scale. The input data of the neural network is a grayscale image expressing the building elevation, and the real-time output data is a pseudo-color map of wind pressure and solar radiation at pedestrian height, which is sufficient to assist architects in intuitively perceiving the impact of building layout on the urban wind and heat environment (Figures 21 and 22) so as to optimize the urban form more comprehensively [62]. The algorithm is integrated into the latest Giraffe urban design platform as a toolkit for calculating the comfort of the ground wind environment. Its rapid performance feedback has aroused widespread discussion in the architectural community [3]. The SOM algorithm also has applications in this regard. Relying on Mathematica numerical calculation of the SOM neural network for CFD fitting, three-dimensional wind field data is quickly generated [18]. Thomas Wortmann and other scholars developed a meta-heuristic optimization algorithm based on the meta-model idea, and based on this, developed an optimization plug-in Opossum in the Grasshopper platform. Compared with traditional optimization algorithms such as genetic algorithms, this optimization algorithm can obtain better performance optimization results with a smaller number of iterations [35].

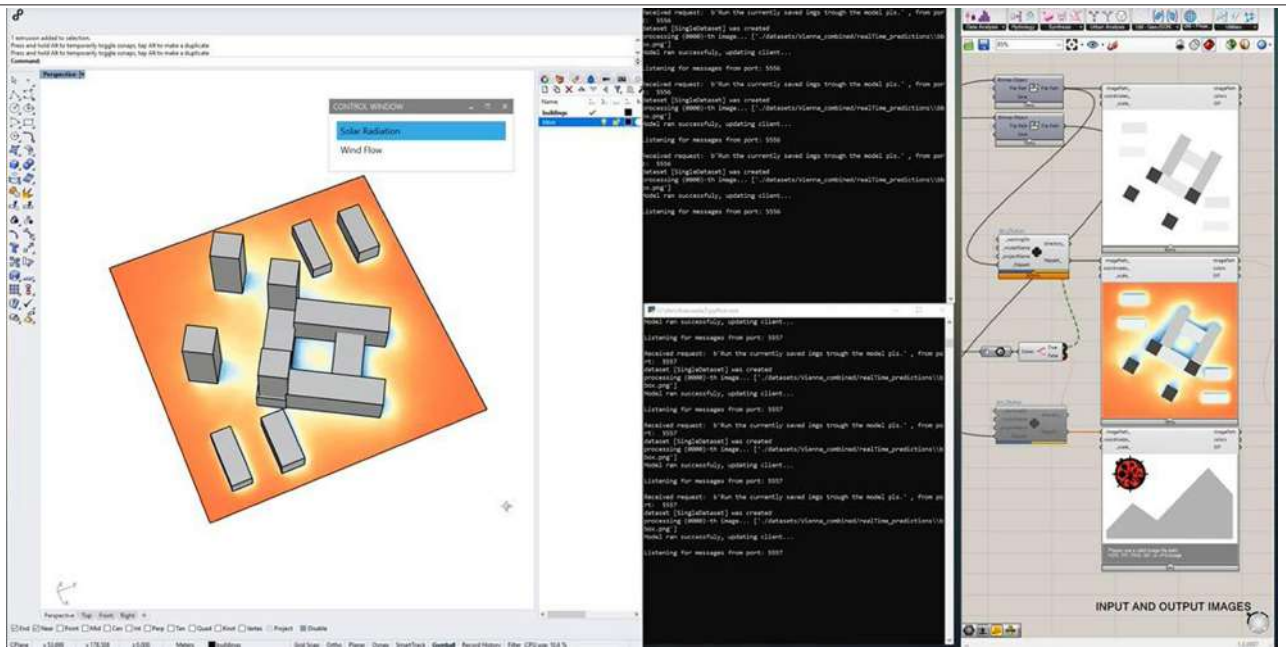

Figure 22 Real-time building sunlight effect prediction results based on the city elevation grayscale image - system interface based on Rhinoceros3D+grasshopper

4 Application path of machine learning methods

Currently, the research and application of machine learning for architects are still in their infancy. This section introduces the machine learning tools and interfaces that architects can use at this stage, as well as the corresponding typical application paths.

4.1 Machine Learning Toolkits and Software

Currently, there are various mature machine learning algorithm toolkits with different focuses. Toolkits such as Accord.NET Framework, NeuronDotNet.dll, AForge.Neuro.dll/NLOptDotNet.dll are lightweight .NET-based machine learning algorithm packages. When writing plug-ins, the corresponding .dll files can be directly called to implement machine learning algorithms. However, these tools cannot complete complex machine learning tasks such as deep learning, nor can they call GPUs for high-load machine learning calculations. Python, as a "glue language"[4] is favored by machine learning engineers. Scikit-learn, as a general machine learning algorithm framework in the python environment, provides a large number of modular solutions for executing machine learning algorithms for data mining and analysis, covering almost all mainstream machine learning algorithms, but it is not optimized for the current popular deep learning technologies. Currently, the widely used frameworks in the field of deep learning are Keras, tensorflow, pytorch, Caffe, etc., which can flexibly build customized deep learning neural networks through python interfaces. At present, most deep learning-related research is based on the above deep learning frameworks. MATLAB, as a widely used software in the engineering field, also includes a machine learning module. The MATLAB API can realize real-time data transmission between MATLAB and external engineering design software.

4.2 Implementation of machine learning without 3D modeling software

The current mainstream machine learning research focuses on the processing of big data media materials such as images and texts. Directly using such media materials to solve relevant problems in the field of architecture does not require the participation of 3D modeling software. For example, in the relevant research of scholars such as Zheng Hao [53] andSteinfeld [58], floor plans and street view pictures are used as input and output media, and classic styleGAN, Pix2PixHD and other two-dimensional image-based machine learning algorithm packages are used to generate the required two-dimensional image results. The entire process is directly implemented using the Python programming platform.

4.3 Implementation of machine learning based on 3D modeling software

There are two main paths to implement machine learning algorithms based on 3D modeling software: plug-in tools provided by the modeling software; data exchange between 3D software and mature algorithm platforms.

The plug-in tools provided by the softwareinclude the machine learning algorithm, which does not require designers to perform custom programming, so machine learning algorithms can be quickly integrated into the design process. There are several third-party algorithm grasshopper plug-ins under the Rhinoceros3D platform that support the implementation of machine learning algorithms: opossum optimization plug-in [83] [84], Lunchbox, Owl, Crow, Dodo, ANT plug-in, etc. (Table 2) (Figure 23). Due to the limitations of the software platform, the above plug-ins cannot be linked to GPU for parallel computing, and the setting and modification of their parameters are limited, and the adjustment of these parameters is often the most important issue in neural network design [85]. The Lunchbox plug-in also has a Dynamo platform version based on Revit, which includes the same machine learning algorithm as the grasshopper platform.

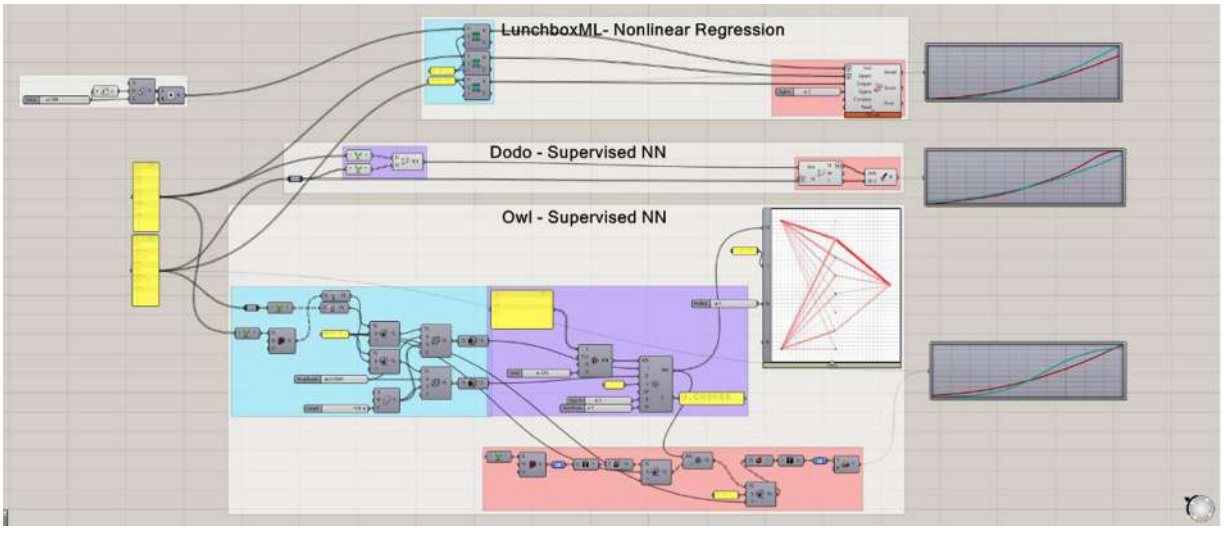

Figure 23 Single-layer neural networks built using LunchboxML, Dodo, and Owl plugins

Table 2 Grasshopper plugins that support machine learning algorithms

Grasshopper plug-in	Relevantarithmetic libraries	Details of machine learning implementation
Opossum	RBFOpt	Implementing a single-objectiveoptimization algorithm based on the "surrogate model" using the RBF neural network.
Lunchbox	Accord.NET Framework	Solves regression problems, clustering-related problems, and builds neural networks; each algorithm is packaged into different operators, which is easy to use, but the algorithm parameters cannot be adjusted in detail (for example, the neural network operator defaults to a single hidden layer network, and it is impossible to write a multi-hidden layer network).
Owl	Accord.NET Framework	Based on the neural network design of visual programming, it can perform tasks such as two-dimensional image recognition, reinforcement learning, and cluster analysis. The construction of the algorithm program requires a certain background knowledge of neural networks.
Crow	NeuronDotNet.dll	Simple forward pass neural network construction (currently only supports classification prediction problems) and SOM self-organizing neural network construction.
Dodo	AForge.Neuro.dll/ NLOptDotNet.dll	Can realize simple forward pass neuralnetwork but does not support discrete data classification problems.
ANT	Scikit-learn	Implements SVM, regression analysis and other functions, and the functions are relatively comprehensive.

There are two ways to exchange data between 3D software and external machine learning tools: through plug-in communication and through file exchange. In the Rhinoceros3D platform, the Ghcpython and ghpython remote plug-ins can directly call machine learning related computing libraries such as numpy, scipy, keras, tensorflow, etc. in the grasshopper interface, which is convenient for establishing a seamless machine learning process; in Revit's Dynamo platform, Python and C# programming languagescan be used to achieve the above data exchange. The PDG parametric platform in Houdini is based on Python language and can also link to classic machine learning algorithm libraries such as tensorflow and pytorch, and its official website introduces a fast terrain generation method based on machine learning [86]. In addition, exporting the data in the 3D software in .csv and other formats is also convenient for calling on Python platforms, MATLAB and other computing simulation platforms, but the storage and reading of exchange files will take a lot of time, which will become a speed bottleneck when processing ultra-large-scale data.

Professor Sun Cheng's team in China proposed a design model for collaborative scheme creation between artificial intelligence andarchitects and used deep learning technology to develop an intelligent design system (Quick Design Generator) that realizes human-machine collaborative scheme design. This system is a typical machine learning implementation method based on 3D modeling software - it converts the three-dimensional architectural data into two-dimensional information in Grasshopper, uses Python language to link the Grasshopper parametric platform with the TensorFlow machine learning framework, combines two-dimensional architectural imagery pictures for style transfer and feeds them back to Grasshopper to generate three-dimensional volumes. This method successfully integrates the architectural design intention features into the three-dimensional architectural volume, assisting designers in scheme creation [74].

5 Conclusion

This paper systematically combs through the cutting-edge research on machine learning and neural network technology in the current field of architecture to represent the application of this advanced technology in the field of architecture as much as possible. Based on the above analysis, we can conclude that the current status and future research trends of machine learning technology in the field of architectural design can be summarized into the following five aspects:

(1) Traditional machine learning tools such as ANN, SVM, and PCA are widely used in the field of architectural engineering. Although they do notboast the "magic" of deep learning technology, they still have great application potential in the field of performance optimization. As shown by the research of Tongji University [33], the use of machine learning technology to couple quantitative building performance indicators with building form characteristics and quickly provide performance feedback is more in line with the needs of increasingly "intelligent" buildings.

(2) Machine learning algorithms based on two-dimensional images (neural network structures such as CNN/GAN) have great potential in expanding the creativity of architects. With the deepening of related research, the intervention of these machine learning algorithms will become more practical. This practicality has been initially revealed in the direction of architectural form creativity [74][73].

(3) How to faithfully translate the three-dimensional information of a building into data that can be "understood" and operated by machine learning is an important research direction. High-fidelity three-dimensional architectural information processing will greatly promote machine learning applications related to architectural form.

(4) Under the premise of using machine learning as an auxiliary tool, different machine learning algorithms can be used in combination throughout the design process to improve designefficiency [21], and different machine

learning algorithms should be screened to obtain the best performance [9][65].

(5) Although the current mainstream 3D modeling platform has introduced a number of machine learning algorithm plug-ins, the current mainstream machine learning algorithm application still relies on classic machine learning algorithm libraries such as tensorflow and pytorch. The method of linking 3D modeling software with machine learning algorithms based on language interfaces such as python willbe the mainstream for a long time.

Architecture is a discipline that combines art and engineering.Therefore, Architects should consider both aesthetic needs and architectural performance requirements. Machine learning and neural network related tools provide architects with the ability to present complex problems from an intuitive data perspective. Its powerful data integration and feature recognition capabilities can also assist architects in rapid and exhaustive solution optimization. These powerful tools can help liberate architects from the boring comparative trial and error, transform the current "labor-intensive" design into "intelligence-intensive" design, and help architects focus more on the intangible elements of architecture, find a better balance between building performance requirements, design aesthetics and social concerns, and expand the boundaries of architecture.

Figure and table sources

Figure 1: Reference [3]

Figure 2: Reference [2]

Figure 3:Drawn by the author

Figure 4: Reference [17]

Figure 5: Reference [7]

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Figure 7: Reference [8]

Figure 8: Reference [36]

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Figure 12: Reference [59]

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Figure 14: Reference [45]

Figure 15: Reference [75]

Figure 16: Reference [76]

Figure 17: Reference [47]

Figure 18: Reference [25]

Figure 19: Reference [16]

Figure 20: Reference [60]

Figure 21: http: // cities.ait.ac.at/site/index.php/2019/05/29/wind-flow-prediction-through-machine-learning/

Figure 22: http: // cities.ait.ac.at/site/index.php/2019/04/11/solar-radiation-prediction-through-machine-learning/

Figure 23:Drawn by the author

Table 1 and Table 2: Drawn by the author

Notes

1) In supervised learning and semi-supervised learning tasks, the machine learning algorithm receives a set of labeled data during the training phase. The trained machine learning algorithm can guess possible labels based on the newly input unlabeled data. For example, in the training phase of the animal image recognition task, the input labeled data is the image of the animal and the corresponding animal species label. These labeled data usually need to be annotated by humans/experts.

2) Compared with linear structures and tree structures, graph structures are complex nonlinear structures. Graph structures are composed ofvertices and edges. Edges represent the connection between vertices; any two vertices in the graph structure may be connected by edges. Depending on whether the edge is directional, the graph structure is divided into directed graphs and undirected graphs. Graph structures can be used to model many complex systems, such as knowledge graph relationships, social relationships, transportation networks, computer networks, consumer markets, etc.

3) Giraffe is an online urban design platform, official website address: https: // www.giraffe.build/

4) Glue language refers to a language that is used to con-

nect various software components to realize the overall business process (handy like glue). It only acts as an intermediate processing module to call various core programs written in other languages and perform comprehensive processing. Python is suitable as a glue language because it has extremely high code readability and flexible syntax as a scripting language, and has a rich third-party library.

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The Impact of Greenway Environment on Residents' Use Intensity from the Perspective of Health

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ABSTRACT: The conversion of the health benefits of the greenway space needs to be completed by residents' use, and different environmental composition characteristics will directly affect the user's use intensity. Based on the perspective of health needs, taking the greenway area of Jiulongpo District, Chongqing City as the research object, based on existing research and field investigation, quantitative analysis and evaluation of the environmental characteristics of the greenway and the intensity of residents' use are carried out. The research results show that: 1) The environmental characteristic factors that affect the attractiveness of the greenway mainly include environmental coordination, suitable sites, recreational facilities, and unobstructed walking; 2) There are significant differences in the frequency and duration of use of different environmental elements in the greenway for the interviewees. There is a positive correlation between the frequency of use of greenways by unobstructed walking, landscape art, safety protection, suitable venues, and recreational facilities, and there is a positive correlation between landscape art, environmental coordination, suitable venues, and recreational facilities and the length of single use. In order to build a greenway environment that promotes healthy behavior activities, space optimization suggestions are put forward from four aspects: accessibility, landscape features, activity venues and recreational facilities, and safety protection.

KEY WORDS: urban greenways; environmental characteristics; health needs; intensity of use

1 Introduction

The incidence of chronic diseases, mental illnesses and other health problems is gradually increasing in our country, which has seriously threatened the health of Chinese residents and affected the country's economic and social development [1-3]. The "China Medium- and Long-Term Plan for the Prevention and Treatment of Chronic Diseases (2017-2025)" proposed that creating a healthy and supportive environment and building a healthy production and living environment are important ways to control the occurrence of chronic diseases. The 2019 "Opinions of the State Council on Implementing the Healthy China Action" further pointed out that building a healthy environment and advocating a healthy and civilized lifestyle are conducive to the prevention and control of major diseases. In the face of the current reality of increasing work and life pressure, creating modern living spaces and places that relieve mental stress and encourage walking is an important way to help overcome the occurrence of health diseases. Urban green space is a significant environmental factor for a healthy lifestyle [4]. By providing

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outdoor recreational and leisure venues, the urban green space allows urban residents to relieve stress in the process of getting close to nature, and promotes physical health by stimulating residents' fitness behaviors [5]. A green and low-carbon lifestyle can also better meet travel needs. As a key part in our country's urban ecological construction, greenways have the characteristics of small footprint, wide coverage and strong connectivity, which can make up for the lack of green space in developed urban areas. The unique linear characteristics of greenways can connect existing green spaces in cities to maximize the function of natural landscapes, create open space corridors, and increase the use opportunities by combining with the construction of urban transportation systems. A large number of studies have confirmed that the conversion of health benefits of green spaces depends on the use of residents [6-9]. Residents who use green spaces for a long time are much less likely to feel stress. The higher the frequency of using public green spaces, the lower the probability of suffering from diseases related to mental stress [10-11]. Comparing frequent exposure to natural environments with frequent contact with urban environments, the former can promote people's physiological conditions (lower blood pressure), improve cognitive ability, enhance happiness, and reduce excitement [12]. Therefore, exploring the greenway environment that affects residents' use has a strong research significance for creating a healthy lifestyle.

At present, the relationship between greenways and residents' use focuses more on accessibility analysis and landscape environment quality. The former studies highlight the inspiration for greenway route selection and design. For example, Zhu Zhanqiang et al. used a multivariate linear regression model to explore the relationship between the built environment around the greenway and the use of the greenway from the perspective of "greenway-neighborhood," and the results showed that the built environment around the greenway affects its use effect, as the surrounding land use mix and residential population density can affect the intensity of greenway use [13]. Zhu Jiang et al. conducted an empirical study on the slow-moving system in the Pearl River Delta region through correlation analysis and structural equation modeling. The study found that accessibility is an important factor affecting residents' use, which should be used to guide residents' travel preferences in traffic design [14]. The research on landscape environment focuses more on exploring environmental attractiveness. For example, Fan Rong et al. used drone aerial photography tools and eCognition intelligent image analysis methods to construct a model of the visual attraction characteristics of greenway landscape space and found four characteristics of greenway landscape space visual attraction: significance, selectivity, positivity and repetitiveness [15]. Gao Yushi et al. took the 198 LOHAS Greenway in Jinjiang, Chengdu as an example, applied the POE method and conducted a coupling analysis of its conclusions and the spatial participation and landscape preference of users at each node of the greenway. They found that the organic combination of ecology and recreation can enhance the attractiveness of open space [16]. The research on the relationship between greenways and residents' use characteristics has made considerable progress, but the impact of internal environmental factors on the use frequency of users in the built greenways is still lacking. At present, the construction of greenways in our country is in full swing, but there are still problems such as environmental homogeneity leading to low overall use efficiency or even abandonment [17-18]. How to further deepen the existing research and explore the influence mechanism between the two can improve residents' recreational experience, increase use intensity, and accelerate the delivery of health benefits. In view of this, this paper takes the Jiulongpo Greenway as the research object, conducts a quantitative analysis and evaluation of the attributes and use characteristics of greenway users through a questionnaire survey, and puts forward specific suggestions for the optimization of greenway space in a targeted manner. The research results can provide an important basis and reference for the optimization and improvement of greenways.

2 Research Methods

2.1 Selection of influencing factors

The health benefits of greenways are to provide residents with a space for healthy behaviors, ensure that they

can relieve negative emotions, increase physical activity and social interaction in the greenway, and ultimately promote positive adjustments and recovery in psychological state, physiological level, behavior and cognitive function. Therefore, the effect of greenway environment on residents' health benefits is affected by the following factors:

(1) Greenway environmental characteristics

From the perspective of the health benefits that greenways can provide to residents, their environmental characteristics (such as landscape perception, facility services, and maintenance) can be divided into three categories: landscape elements, facility elements, and service elements. Landscape elements (such as beautiful scenery, naturalness, vegetation and waterfeatures) can affect the use of greenways [19], and the quality of the environment can directly affect the subjective well-being of users [20]; facility elements (such as road paving, benches, landscape pavilions, activity spaces, etc.) can increase the attractiveness of green spaces [21] and increase the length of time users spend there [22]; maintenance of greenways (such as safety protection, public security management, etc.) can affect users' subjective perception and is also an important factor in measuring a healthy outdoor environment [23]. Green spaces with low maintenance levels will affect the frequency of use by residents [24].

(2) User behavior patterns

The acquisition of health benefits is closely related to the user's behavioral activities. Studies have shown that participating in physical activities (such as walking and jogging) can improve mental health and physical health more than participating in other activities (such as reading and going to clubs) [25]. In addition, walking in green spaces has higher benefits than walking indoors [26]. Combining relevant research and actual survey results, the user behavior patterns in the greenway are finally divided into sports and fitness (running, walking, equipment exercise), leisure and relax (seeing the scenery, learning history and culture, relieving stress), and social entertainment (staying with friends or family, dancing, chess and cards).

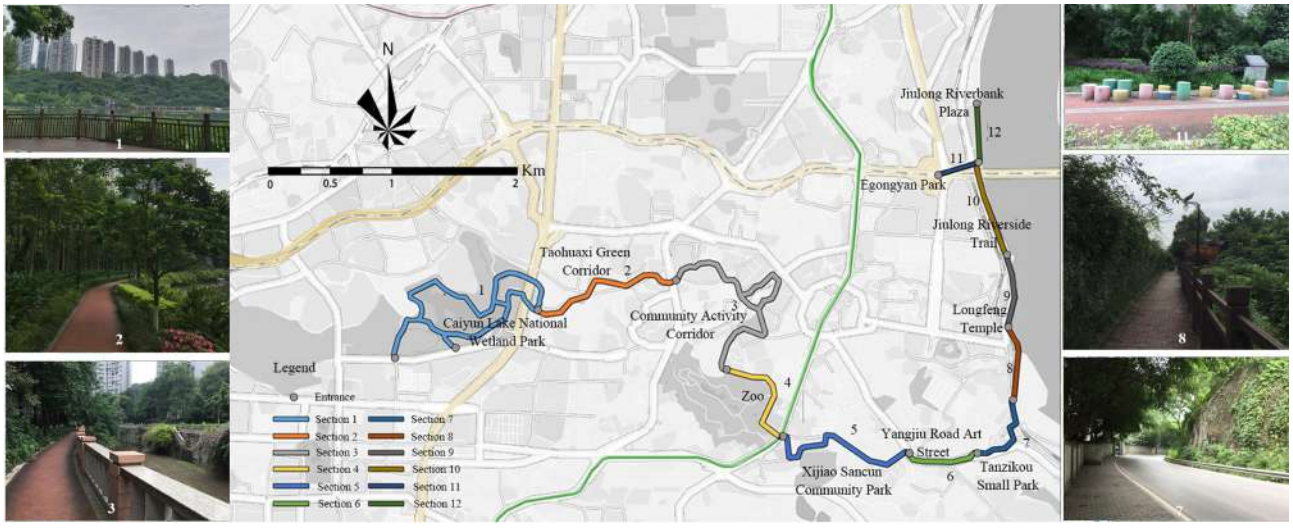


Figure 1 Plan of Jiulongpo Greenway

2.2 Questionnaire and scale design

A questionnaire survey method was used to collect dataand record the age, gender, activity type, duration and weekly frequency of users along the greenway during the peak period of greenway use (17:30-21:30 on weekdays and 09:00-21:30 on weekends). Through face-to-face interviews, data from three aspects were collected: 1) the socioeconomic attributes of the respondents (age, gender, education level, income level); 2) the environmental characteristics of the greenway (landscape elements, facility elements, service elements). The selected indicators (Table 1) were explained to the respondents before the evaluation; 3) residents' usage preferences (the degree of attraction of environmental characteristics to residents) and usage characteristics (duration of use, frequency of use). The questionnaire mainly adopted the chance sampling method. The

survey time was from October 6, 2019 to October 13, 2019, and 273 valid questionnaires were obtained.

Table 1 Indicators in the quetionnaire

	Measurementindicator	Definition
Landscape elements	Adequate lighting	Whether the venue is equipped withenough street lights and landscape lighting facilities
	Clear signs	Are the indicator devices around the venue (the start of the greenway, important node signs, entrance and exit signs) clear
	Ease of walking	Is there any traffic interference in the venue, and is the accessibility smooth
	Comfortable paving	Is the paving material suitable for walking
	Landscape art	Is the cultural landscape in the greenway unique (whether the landscape nodes have the regional characteristics of Chongqing)
	Environmental coordination	Is the landscape in the greenwayornamental (vegetation richness, color diversity, seasonal variability, etc.)
Facilityelements	Suitable venues	Is the sufficient activity space in the greenway
	Recreation facilities	Is the venue equipped with ordinary seats, pavilions, corridors, flower stands and otherrest facilities
	Sanitation facilities	Whether the venue is equipped with sufficient trash cans
Service elements	Safety protection	Whether the venue has safety protection facilities (such as safety guardrails near the car lane, safety guardrails on the overhead walkway, complete lighting equipment, etc.)
	Public security management	Can you call for help in time if there is danger in the venue

2.3 Research Methods

This paper measures the intensity of greenway use through two aspects: first, the degree of attraction of the current environmental characteristics of the greenway to users, that is, whether users are willing to carry out activities in the greenway; second, the frequency of respondents' weekly use of the greenway and the duration of each use of the greenway, and finally the time users are willing to spend in the greenway each week.

2.3.1 The attractiveness of environmental characteristics to residents' use behavior

The 11 environmental characteristics are measured and evaluated using the Likert 5-point scale. The survey content includes"Based on the current environmental composition of the greenway, will these environmental factors attract you to enter the greenway to carry out activities? (1 = very bad, 5 = very good)," and descriptive statistics (mean size) are used as the performance of the environment. The study used KMO and Bartlett's sphericity test to obtain a KMO value of 0.727 and a sig. value of 0.00, indicating that the data sample is sufficient, there is a correlation between the variables, and it is suitable for factor analysis. In order to eliminate the impact of the average value, the coefficient of variation is used to test the consistency of user cognition (Table 2), and the first three factors with a cumulative variance contribution rate greater than 72.61% are selected, and the weighted summation and normalization processing are used to obtain the weight value of each factor (Table 3). Finally, the weighted summation of the factor weight value is used to obtain a comprehensive evaluation of the impact of environmental factors on users.

2.3.2 Greenway usage level

The time users are willing to spend on the greenway each week is taken as their greenway usage level, and finally the usage level of 12 sections of greenways is obtained (Figure 4).

$$p = \frac{\sum_{i=0}^{n} t_i * f_i}{n} \qquad \text{(Formula 1)}$$

Note: t_i is the weekly usage time of the i-th person, f_i is the weekly usage frequency of the i-th person, and n is the total number of people

3 Results Analysis

3.1 Analysis of User Attributes and Purposes

As can be seen from Figure 2, the proportion of females is 52.75%, slightly higher than that of males at 47.25%; in terms of age structure, the largest number of people aged 45-60, accounting for 24.18%, while those under 18 (9.16%) and over 60 (9.89%) accounted for smaller proportions; in terms of education level, the proportion of

people with vocational education or above was the highest (58.24%), and the overall education level was relatively high; in terms of income level, the low-income group (monthly income ⩽ 3,000 yuan) accounted for 20.51%, the middle- and high-income groups (3000 ⩽ monthly income ⩽ 7000 yuan) accounted for the highest proportion of 63.74%, and the high-income group (monthly income ⩾ 7000 yuan) accounted for 15.75%; in terms of the purpose of use, the proportions of people using the greenway for leisure and relax (33.97%) and sports and fitness (33.67%) were relatively high, and there were also some using it for commuting and shopping (19.05); the proportion of people using the greenway more than twice a week was 79.49%, and the proportion of people staying in the greenway for 15-60 minutes was 79.49%.

Table 2 Total variance explained

Total varianceexplained									
Component	Initial eigenvalue			Extracted sum ofsquares of loadings			Rotated sum of squares of loadings		
	Total	Variance percentage	Cumulative/%	Total	Variance percentage	Cumulative/%	Total	Variance percentage	Cumulative/%
1	5.630	51.184	51.184	5.630	51.184	51.184	4.366	39.692	39.692
2	1.353	12.299	63.483	1.353	12.299	63.483	2.536	23.058	62.750
3	1.004	9.124	72.606	1.004	9.124	72.606	1.084	9.856	72.606
4	.831	7.556	80.163						
5	.546	4.963	85.126						
6	.493	4.482	89.607						
7	.425	3.865	93.472						
8	.322	2.927	96.399						
9	.193	1.752	98.151						
10	.145	1.317	99.469						
11	.058	.531	100.000						

Table 3 Weightranking of each factor

Dimension	Factor	Mean	Coefficient of variation	Common factor variance extraction	Weight	Order
Environmental quality and safety	Adequate lighting	3.36	26.85%	.810	0.0942	5
	Clear signs	2.48	36.61%	.700	0.0852	6
	Ease of walking	3.91	16.01%	.640	0.1044	4
	Comfortable paving	3.73	23.89%	.557	0.0803	9
	Landscape art	3.85	20.34%	.631	0.0807	8
	Environmental coordination	3.66	23.50%	.947	0.1185	1
Facilities	Suitable venues	4.1	22.00%	.684	0.1178	2
	Recreation facilities	3.9	23.13%	.683	0.1146	3
	Sanitation facilities	3.85	17.56%	.563	0.0812	7
Maintenance and management	Safety protection	2.95	36.44%	.839	0.0759	10
	Public security management	2.22	34.41%	.931	0.0472	11
	Overall attractiveness	3.42	11.44%			

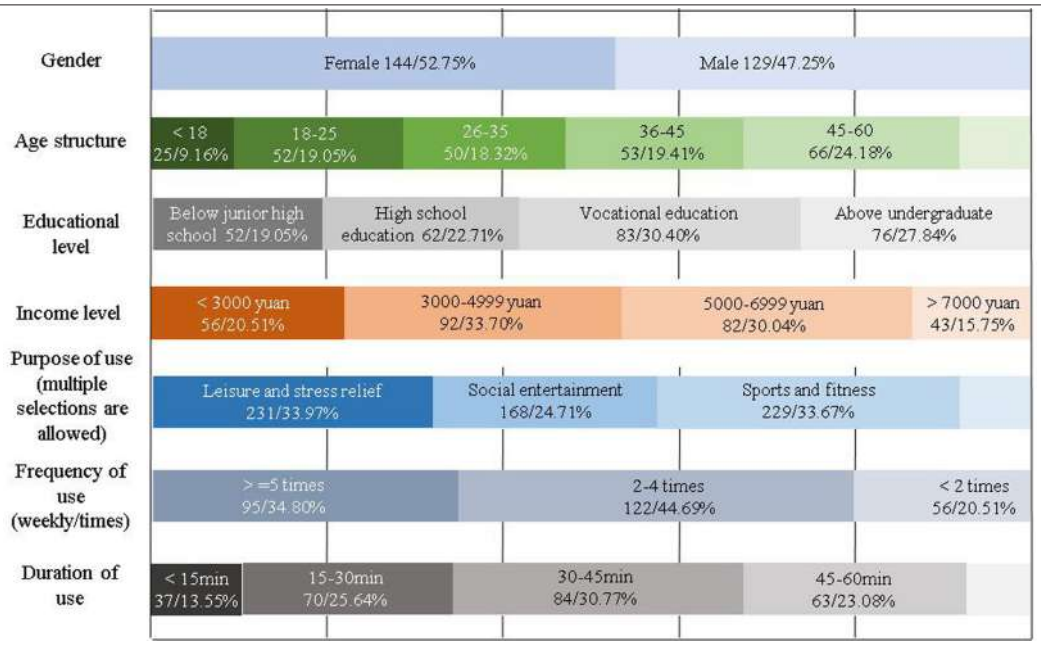
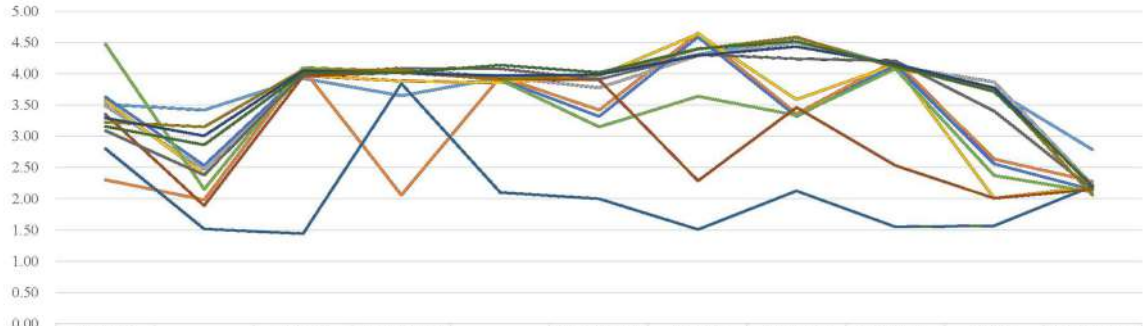


Figure 2 Social demographic characteristics of the respondents

3.2 Evaluation of the attractiveness of the environmental factors of Jiulongpo Greenway

3.2.1 Evaluation of the attractiveness of individual environmental factors

From the perspective of the performanceof individual factors of the environment, the high average values of suitable venues, recreational facilities, comfortable pavement, ease of walking, and landscape art can better serve users, while the low average values of sign system, public security management, and safety protection indicate that the current status is poor. In addition, the coefficients of variation for ease of walking (16.01%) and sanitation facilities (17.56%) were relatively small, indicating that users had a high degree of consistency in their performance evaluation of these two items; while the coefficients of variation for clear signs (36.61%), safety protection (36.44%), and public security management (34.41%) were relatively large, indicating that the respondents had large differences in their opinions about these three factors. Combining the sample description (Figure 3) with the field interviews, it can be inferred that there are two reasons: 1) There are differences in individual subjective cognition. Taking the clear sign factor as an example, in the current Jiulongpo Greenway sign system, only the greenway starting and ending points (Caiyun Lake Wetland Park and Egongyan Park points), are map marks combined with written introductions. The rest of the sign points are simple names and direction markings, especially for special mountainous terrains, which cannot provide effective guidance. From the perspective of public security management, the overall score of the greenway is currently low (2.22), and the average of different sections is also low. There are significant differences in public security management between individuals. Female groups, especially those with children, have more urgent safety needs, which also reflects that the Jiulongpo Greenway urgently needs to be optimized and improved in terms of public security management; 2) The performance of the two factors of safety protection varies significantly between different greenway sections (the highest is 3.87, the lowest is 1.57). From the distribution of greenways, the 7th section (1.57) and the 8th section (2.01) perform poorly in safety protection. In the on-site survey, it was found that the current pedestrian path of the 7th section of the greenway is narrow and there is no safety isolation due to the large slope and the difficulty of optimization, which leads to safety hazards. The 8th section of the greenway is adjacent to the railway track, and there are some greenway walking widths less than 1m and the guardrails on one side are short, which are dangerous for children, so it needs to be paid attention to.



	Adequate lighting	Clear signs	Ease of walking	Comfortable paving	Landscape art	Environmental coordination	Suitable venues	Recreation facilities	Sanitation facilities	Safety protection	Public security management
Section 1	3.51	3.42	3.93	3.65	3.94	4.00	4.31	4.58	4.13	3.74	2.79
Section 2	2.30	1.98	4.08	2.06	3.95	3.42	4.65	3.36	4.21	2.63	2.28
Section 3	3.49	2.47	3.98	4.06	3.95	3.78	4.29	4.50	4.12	3.87	2.22
Section 4	3.57	2.39	3.97	3.89	3.86	3.97	4.64	3.59	4.15	2.01	2.19
Section 5	3.63	2.53	4.02	4.03	3.91	3.32	4.59	3.32	4.14	2.56	2.14
Section 6	4.48	2.15	4.10	4.04	3.90	3.15	3.64	3.34	4.08	2.37	2.11
Section 7	2.80	1.52	1.44	3.84	2.10	2.00	1.51	2.13	1.55	1.57	2.20
Section 8	3.35	1.89	3.96	4.02	3.92	3.90	2.29	3.46	2.53	2.01	2.15
Section 9	3.09	2.38	4.00	4.09	4.08	3.91	4.31	4.24	4.21	3.40	2.15
Section 10	3.23	3.15	4.06	4.06	3.90	4.00	4.39	4.59	4.10	3.77	2.06
Section 11	3.29	3.01	4.05	4.01	3.97	3.99	4.29	4.44	4.16	3.78	2.19
Section 12	3.16	2.86	4.01	4.01	4.14	4.02	4.40	4.52	4.12	3.72	2.21

Figure 3 Performance of attractiveness of each factor in greenway segment

3.2.2 Overall attractiveness evaluation of the greenway

As shown in Table 2, the average value of the overall attractiveness of greenway to the respondents is 3.42, and the coefficient of variation is 11.44%, indicating that the overall attractiveness of greenway to users is relatively large, and the level of cognitive consistency is high, which also shows that the planning and construction of Jiulongpo Greenway is relatively successful. The weight ofan environmental characteristic evaluation factor can characterize the influence of this factor on the overall attractiveness of greenway. As shown in Table 2, the four factors with the largest contribution rate to the evaluation of the current attractiveness of greenway are environmental coordination (11.85%), suitable venue (11.78%), rest facilities (11.46%), and ease of walking (10.44%), which shows that the factors affecting the level of attractiveness of greenway to users are mainly concentrated in the service function of greenway, whether there are sufficient activity venues and rest facilities (pavilions, seats, etc.), environmental quality and walking accessibility.

3.3 Analysis of usage level of Jiulongpo Greenway

3.3.1 Comparison of usage duration and usage frequency betweenthe sections

At present, there are significant differences in the usage levelsbetween the sections Jiulongpo Greenway, and the overall spatial pattern is "more in the west and less in the east" (Figure 4). Among them, there are 5 greenway sections with high usage levels calculated through Formula 1: section 1 has the highest usage level (10.46), followed by section 3 (7.94), section 11 (7.53), section 12 (7.38), and section 4 (7.20). The reason is that the western sections of the greenway have the highest level of use. Among them, Caiyun Lake Park (section 1) has good current landscape conditions and is highly attractive to users. The Taohuaxi Community Activity Corridor Section (section 3) currently has many residences and public services, with complete supporting facilities and sufficient fitness facilities; there is a height difference between the eastern part of the greenway near the Yangtze River and the surrounding roadways (Zhigang Avenue, Jiubin Road), and the entrances to the greenway were few, resulting in limited accessibility. It can be seen that the level of greenway usage is closely related to the environmental characteristics of the greenway itself.

In terms of frequency of use, users ofsection 1 mostly use it more than 5 times a week, users of section 3 mostly use it 2-4 times a week, and users of section 12 and section 4 use it more than 2 times a week. There are large individual differences among users of section 11, which indicates that users may have different purposes of using section 11. In terms of usage time, users of sections 1 and 3 all spend more than 30 minutes, and some users spend more than 1 hour. The usage time of sections 12 greenways is mostly concentrated between 30-60 minutes, and the length of

time users spend on section 11 of the greenway varies significantly among individuals. In addition, the usage frequency of 6 sections is higher than 5 times but the duration is low, suggesting that there may be behaviors such as commuting and shopping, which has nothing to do with the environmental characteristics of the greenway itself.

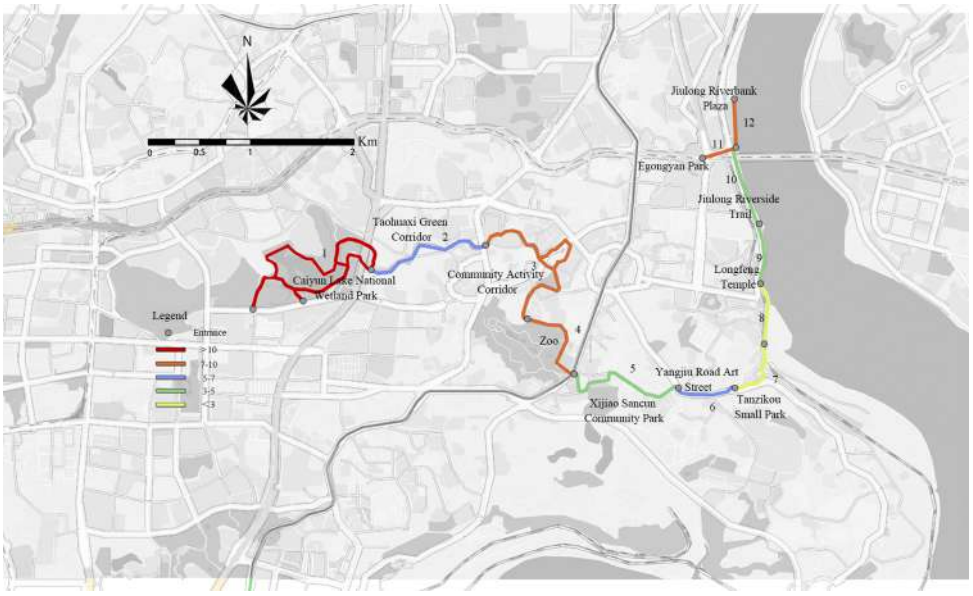


Figure 4 Jiulongpo Greenway usage time analysis chart

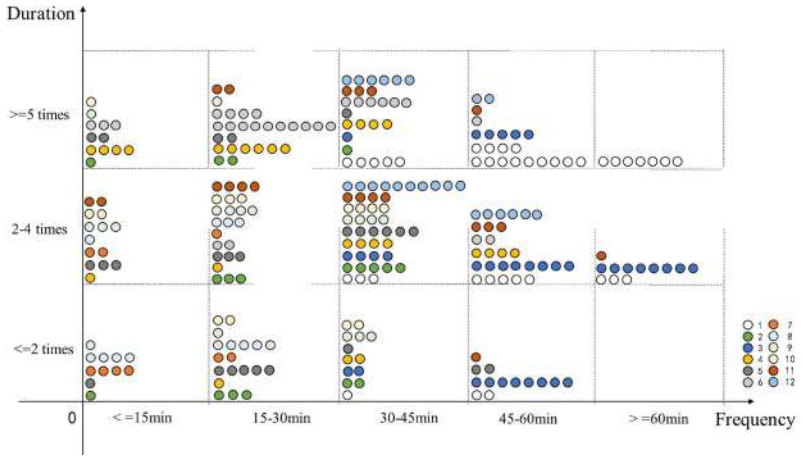


Figure 5 Sample distribution performance chart

3.3.2 Correlation analysis between environmental characteristics, usage duration and usage frequency

As can be seen from Table 4, there are significant differences in the attractiveness of different environmental elements in greenways to respondents in terms of frequency of use and duration of use. There is a positive correlation between the overall environmental quality and supporting facilities of the greenway and the frequency of use of the greenway (0.201^{**}, 0.181^{**}) and the duration of single use (0.326^{**}, 0.243^{**}) of the respondents. Among them, ease of walking (0.220^{**}), landscape art (0.261^{**}) and frequency of use are positively correlated at the confidence zone of 0.01, that is, the stronger the accessibility of the greenway and the more distinctive the landscape, the greater the frequency of use; secondly, landscape art (0.261^{**}), environmental coordination (0.184^{**}) and single use duration are positively correlated at the confidence zone of 0.01, that is, the higher the uniqueness and richer types of the landscape, the longer the respondent's single use duration; suitable venues (0.199^{**}, 0.203^{**}) and recreational facilities (0.304^{**}, 0.15^{**}) in supporting facilities and frequency of use are positively correlated at the confidence

zone of 0.01, that is, the more complete the greenway is with sufficient activity space and recreational facilities, the larger the respondent's frequency of use and the duration of single use; the overall maintenance facilities of the greenway are positively correlated with the respondent's frequency of use (0.380**), among which safety protection (0.423**) and frequency of use show a positive correlation in the confidence area of 0.01, that is, the more complete the adequate safety guardrails and safety prompt facilities in the greenway site, the higher the frequency of use by the respondents.

Table 4 Correlation analysis between individual factors and usage duration and frequency

Environmentalelements		Usage frequency	Sig.(two-tailed)	Singleuse time	Sig.(two-tailed)
Environmental quality		.201**	0.001	.181**	0.003
	Adequate lighting	—	—	—	—
	Clear signs	—	—	—	—
	Ease of walking	.220**	0.000	—	—
	Comfortable paving	—	—	—	—
	Landscape art	.261**	0.000	.213**	0.000
	Environmental coordination	—	—	.184**	0.002
Facilities		.326**	0.000	.243**	0.000
	Suitable venues	.199**	0.001	.203**	0.001
	Recreation facilities	.304**	0.000	.159**	0.005
	Sanitation facilities	—	—	—	—
Maintenance and service		.380**	0.000	—	—
	Safety protection	.423**	0.000	—	—
	Public security management	—	—	—	—

Note: ** means at the 0.01 level (two-tailed), the correlation is significant; * means ast the 0.05 level (two-tailed), the correlation is significant.

3.3.3 The impact of Jiulongpo Greenway environmental characteristics on residents' use level

Taking Jiulongpo Greenway as an example, the study took the attractiveness of the current environmental characteristics of the greenway and the time respondents were willing to spend as the research objects. The study found that: improving environmentalbeauty and pedestrian accessibility will increase the attractiveness of the greenway and increase the frequency of use of respondents; suitable activity venues and sufficient recreational facilities will help psychologically encourage users to actively participate in green space activities and extend their single use time.

In terms of landscape art, the current performance ofsection 1 (Caiyun Lake Park), section 4 (around Chongqing Zoo), and sections 9-10 (Riverside Landscape) is better when comparing the ornamental value of the greenway environment. This shows that the urban trails that connect the existing landscape nodes of the city can rely on the existing high-quality landscape resources to conveniently create an environment that meets the viewing needs of residents. In terms of ease of walking, the network analysis module of ArcGIS was used to buffer the entrance of each section of the greenway along the road, and the walking range of 500m and 1000m was obtained respectively. By comparing the accessibility of each section, it was found that the 500m walking accessibility of sections 3-6 was the highest, and those of sections 9-14 were the worst. The heterogeneity was highlighted and each had its own advantages and disadvantages. First of all, the wide traffic radiation around the greenway sections 3-6 brought convenient accessibility, but on the other hand, the convenience of traffic also caused a certain degree of interference to the sightseeing walking behavior, resulting in a high frequency of use but a short use time for users of this section of the greenway (Figure 6). Due to the influence of the terrain height difference, sections 9-14 have poor connection with the surrounding traffic, but their relatively closed environment also creates a quiet and comfortable walking space. Therefore, the overall use frequency of this section is relatively low, but the single use

time is longer, which shows that the accessibility and walking accessibility of the greenway are equally important in route selection and design. In terms of suitable venues and recreational facilities, by comparing the current activity venues and rest facilities of each section of the greenway (Table 5), it was found that some sections of sections 6-8 lacked fitness facilities and entertainment facilities, while other sections had them arranged, but there were differences in the evaluation scores. It is speculated that the quality of venue and facility arrangement will directly affect the attractiveness of the greenway. By comparing the high-scoring greenways of sections 1, 3, 10, and 12, there common features were found. Concentrated activity venues of sections 1, 3, and 12 were surrounded by appropriate rest seats, and the rest seats of sections 1, 3, and 10 were often set up in combination with small nodes (small landscapes, cultural corridors, historical corridors, etc.).

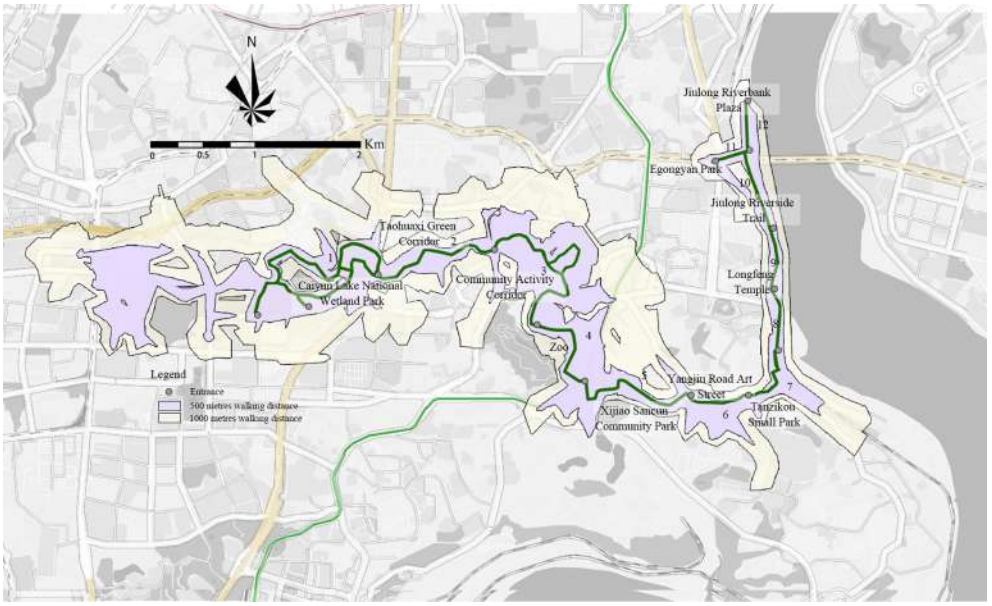


Figure 6 Greenway accessibility analysis diagram

Table 5 Distribution of activity venues and recreational facilities along the greenway

Greenway section	Activityvenues				Recreational facilities		
	Fitness facilities	Entertainment facilities	Activity squares	Plastic fitness tracks	Seats (open-air)	Landscape pavilions (rain shelter)	Landscape bridges
1	□	□	□		□	□	□
2	□	□	□		□	□	
3	□	□	□	□	□	□	
4		□	□		□	□	
5	□	□	□		□	□	
6			□		□	□	
7			□		□		
8	□		□		□		
9		□	□		□		□
10		□	□		□	□	
11		□	□		□		
12	□	□	□		□		
13		□	□	□	□	□	

Note: □ indicates that there are sites or facilities of this type within the greenway.

4 Conclusions and suggestions

The intensity of residents' use of greenways reflects their physical activity level and healthy life quality to a certain extent, and it is closely related to the level of environmental characteristics within the greenway. In the planning and design of greenways, emphasis should be put on the environmental factors of greenways that affect the use intensity, because the use intensity of urban greenways is not only affected by one or two factors, but by multiple factors and their interaction. Starting from users' frequency and duration of use of greenways, the study explored the statistical correlation between environmental characteristics and usage intensity. The research results show that there are significant differences in the attractiveness of different environmental elements to respondents in terms of frequency of use and duration of use. In terms of environmental quality, landscape art will affect the frequency and duration of use by residents. The more prominent the landscape features are, the higher the intensity of use of greenways. Ease of walking will affect the frequency of use by residents. The more accessible the path, the higher the frequency of use by residents. Environmental coordination affects residents' usage time. The more ornamental the landscape, the longer a single usage time. Among the supporting facilities, suitable venues and recreational facilities have an impact on the duration and frequency of residents' use. Sufficient activity space and complete recreational facilities will increase the intensity of residents' use. In maintenance and management, greenways with good safety protection are used more frequently by residents. In view of this, in order to build a greenway environment that promotes healthy behavioral activities, this article puts forward space optimization suggestions from four aspects: path accessibility, landscape features, activity venues and recreational facilities, and safety protection.

(1) Enhance path accessibility and reduce walking interference. From the perspective ofease of walking, urban greenways mainly serve surrounding residents, so their location selection should give priority to the accessibility of their paths. Studies have shown that 79.8% of greenway users live within a radius of 1 kilometer from the greenway. Within the greenway, the closer it is to residences, the higher its utilization rate [27]. Since urban greenways have a wider radiation range, the setting up of convenient public transportation is more conducive to serving urban residents. In addition, the setting of greenways should reduce external interference. For example, Partially closed facilities can reduce the motorized traffic load and the impact of road intersections on the greenway, providing users with a better walking space environment.

(2) Optimize environmental quality and enhance landscape features. Trails with high naturalness can help maximize the health benefits of urban greenways and increase the frequency of users' activities. Creating an environment with regional characteristics can help enhance users' satisfaction and improve their health recovery functions. Therefore, when selecting greenway routes, priority should be given to areas with good green landscape background in the city, connecting existing urban resources and maintaining existing natural landscapes during planning and construction, and on this basis, integrating regional culture and landscapes and pursuing maximized utilization of landscape features. Secondly, in addition to combining the existing cultural characteristic elements of the city, the creation of regional characteristic landscapes also helps to create a cultural sense of the place by exploring the city's characteristic elements.

(3) Create suitable activity venues and equip them with sufficient recreational facilities. Through questionnaire surveys, it was found that the availability of facilities (sports equipment, trails) in greenways directly affects their frequency of use, and the comfort of rest seats directly affects the use of greenways. Therefore, in thedesign of activity venues, attention should be paid to the different recreational motivations of users, and the diversified needs of users should be met. According to different usage purposes and their strengths, different numbers of venues

should be set up to optimize and reasonably divert various types of users to the greatest extent. In the setting of recreational facilities, the seats should be comfortable and safe, a balance between privacy and publicity should be achieved, and the fun of rest should be improved by combining landscape items.

(4) Add protective facilities to improve walking safety. Users are more likely to avoid greenways that are crowded, unsafe, or poorly maintained [28]. From the perspective of the width of the trail, isolation facilities should be installed near the surrounding roadways. For areas with large traffic flow, green isolation can be added to reduce some exhaust gas and noise pollution; from the perspective of the signage system, for special areas (such asgreenway sections with steep slopes) clear warning signs and protective facilities should be installed to ensure walking safety; from the perspective of the lighting system, lighting facilities in the greenway should be regularly maintained to ensure safe use at night.

As a key project of urban ecological construction inour country, greenways have become an important recreational resource in cities due to their small footprint, wide coverage and strong connectivity. The conversion of greenway spaces to health benefits depends on residents' use. Increasing the intensity of greenway use can help create a healthy lifestyle. However, the impact of greenway environmental characteristics on usage intensity is diverse, and the social attributes of different groups and individual usage purposes will have an impact on the research results. This study only investigated how physical and environmental attributes affect the intensity of greenway use, and there is insufficient research on social factors and individual attributes. Therefore, the next step of research should highlight the complex interactions between environmental factors and other factors (such as individuals and society), and explore the cumulative impact and related constraints of urban greenway use, so as to have a more comprehensive understanding of the impact of comprehensive factors on the intensity of urban greenway use.

Figure and table sources

All figures and tables in thepaper are created by the authors.

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