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Volume 1, Number 1 (November 2024)

Contents

Dear Readers,

Welcome to the latest issue of the Journal of Sustainable Built Environment (JSBE). This issue delves into pivotal themes such as architecture and historical preservation, urban planning and development, traffic management, sustainable development, and living environments. Our objective is to elucidate the complexities and opportunities of sustainable development across urban, regional, and global contexts, offering both theoretical insights and practical solutions through multidisciplinary perspectives and innovative methodologies to advance a more sustainable built environment.

As we endeavor to achieve global sustainable development goals, the challenges we face are becoming increasingly intricate and interrelated. Accelerated urbanization, climate change, resource scarcity, and social inclusivity are pressing issues that require our immediate and focused attention. The articles in this issue encompass a broad spectrum of topics, ranging from architecture and historical preservation to urban planning, traffic management, and living environments, presenting diverse academic perspectives to address these challenges. Notably, we feature research on the optimization of industrial building facades through photovoltaic integration, the digital preservation and application of historical building components, the mechanisms underlying shrinkage and expansion in resource-based cities, and the impact of short-haul high-speed rail commuting on land use. These studies contribute profound theoretical insights while offering substantial practical implications.

We particularly advocate for interdisciplinary research and the convergence of academic inquiry with practical implementation, and several articles in this issue exemplify this ethos. For instance, some scholars investigate the potential of smart city technologies to facilitate urban sustainability, while others explore participatory planning as a means to bolster community resilience. We believe these studies will not only inspire the academic community but also serve as valuable references for urban planners, policymakers, and community leaders.

On behalf of the editorial board, I extend my sincere gratitude to all the authors and reviewers who have contributed to this issue. Your dedication and rigorous scholarship enable us to continue advancing the dissemination of knowledge and fostering innovation within the realm of sustainable built environments.

We hope this issue will inspire thoughtful reflection and critical engagement among our readers, and we warmly invite you to join our discourse and contribute to the pursuit of global sustainable development goals.

Happy reading!

Editor-in-Chief

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The Industrial Production and Application of Historical Building Component Heritage from the Perspective of Digital Technology Module Chain

Xing Hang [a,*], Siwei Zhang [b], Jiyu Dang [b]

[a] *Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[b] *Faculty of Architectural Engineering Wuhan University of Bioengineering, 430415, China*

KEYWORDS

digital technology module chain, construction of historical buildings, cultural relics protection, industrial production, education and communication

ABSTRACT

The protection of historical architectural heritage is the key research object of the ancient architecture industry, and the research on the partial construction of buildings is gradually deepening.Nowadays, the use of digital means to research and protect architectural heritage has become an important way for many scholars.However, there are many types of digital software on the market with complex functions, and common digital means include X-spectrum, Jingdiao JDP, point cloud data, 3D printing, etc.Based on the simple construction of dougong, this paper analyzes the method of digital technology module chain, and applies it to the field of architectural construction such as murals and sculptures.This digital technology module chain can not only study and analyze the construction of historical buildings, but also meet the needs of cultural relics preservation, industrial production, education and communication.Finally, it is expected that through the promotion of this digital technology module chain, the protection of historical architectural heritage and cultural communication will be promoted in a more optimized direction.

1. Introduction

In the field of Chinese ancient architecture preservation, the application of digital technologies has become increasingly important, serving as a vital tool in promoting cultural heritage protection.The introduction of virtual reality (VR) technology offers a new perspective for cultural heritage conservation, providing immersive experiences that help the public gain a deeper understanding and appreciation of the cultural value of ancient buildings[1]. Simultaneously, digital methods such as 3D modeling and data storage have significantly enhanced the efficiency and accuracy of architectural heritage preservation[2]. As a cutting-edge tool, 3D printing technology demonstrates enormous potential in the replication and restoration of historical artifacts, not only reducing damage to the originals but also improving the precision of repairs[3].Furthermore, the integration of 3D scanning technology with 3D printing provides innovative solutions for cultural heritage preservation, making the restoration and protection of artifacts more effective[4].Against this backdrop, China's relevant policies and legislative frameworks are continually evolving to promote the integration of digital applications in cultural heritage conservation, ensuring sustainability and social participation[5].These studies highlight the significance of digital technologies in the preservation of ancient architecture and their impact on future conservation efforts.

* Corresponding author at: Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia.
E-mail address: 13003732102@163.com (Xin Hang)

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However, with the continuous emergence of digital software, the diversity, complexity, and lack of cohesion among digital tools make it impossible for any single technology to fulfill the combined demands of research, production, dissemination, and teaching. In this era of rapid digital software development, it is increasingly challenging for a single application to address the needs of the market, research, and education sectors. Amid the uncontrolled proliferation of digital technologies, a modular chain that organizes and connects these tools in an orderly fashion is notably absent. This paper aims to explore a novel digital module that is well-suited for the protection and development of ancient architectural heritage. By advancing the digital transformation of heritage protection, this module is intended to better align with the market demand for industrial production, foster secondary innovation, and enhance communication and educational outreach.

Therefore, this paper primarily investigates the feasibility and sustainable development of the digital module chain through systematic analysis and empirical research, examining its potential for the preservation, production, and dissemination of ancient architectural heritage. By studying simplified dougong structures and promoting applications in murals, sculptures, and other handicrafts, this research demonstrates the value of the digital module chain, providing a modular approach to operation and management in an era of continuous digital advancement.

This paper examines the modular chain facilitating the transition from ancient architectural heritage preservation to industrial production, the modular chain connecting heritage preservation to subsequent research, and the modular chain linking industrial production to cultural dissemination. Additionally, the verification and adaptation of various models aim to enhance the relevance of historical heritage to social demand and supply.

2. Literature review

Over the past two decades, digital technologies such as 3D scanning, 3D printing, Building Information Modeling (BIM), and X-ray spectroscopy have dramatically transformed the field of cultural heritage preservation. These techniques offer detailed documentation and precise restoration methods that have redefined approaches to preserving historical structures and artifacts. This review synthesizes recent research on the application of these technologies in cultural heritage, highlighting both their advancements and limitations.

2.1. Application of point cloud data

3D digitization techniques, as examined in studies by Ioannides and Magnenat-Thalmann, have provided highly accurate models of cultural artifacts that can be stored digitally for future restoration efforts[6].The strength of these technologies lies in their ability to capture intricate details without physically interfering with the object.However, the high costs associated with equipment and the expertise required for 3D modeling present significant barriers[6][7].Future developments could focus on reducing costs and making the technology more user-friendly, potentially through the integration of open-source software[6][8].

Point cloud data has also been employed in creating digital Building Information Models (BIM) for historical buildings.Karasaka and Ulutas demonstrated how point cloud data enhances the accuracy of H-BIM, allowing for better analysis of structural integrity[8].Despite its effectiveness, challenges arise in managing large datasets and ensuring the resolution of scans is sufficient for detailed modeling[9].Research suggests that automating parts of the modeling process could reduce the time and expertise needed for such projects[8][9].

2.2. Application of 3D printing technology

The role of 3D printing in the restoration of architectural elements has grown, with several studies exploring its potential to replicate damaged components with a high degree of accuracy[11].Prieto and Kumar's work highlights the ability of 3D printing to reproduce complex architectural features, though limitations remain concerning the durability of printed materials compared to original building materials[11][12].Advances in material science could help develop more resilient and environmentally friendly 3D printing materials[11].

In combination with 3D printing, X-ray spectroscopy has proven to be a valuable tool for non-invasive material analysis.X-ray spectroscopy enables conservators to identify the composition of materials in historical objects, aiding in the development of appropriate restoration methods[13].However, the reliance on specialized equipment, which is often expensive and requires controlled environments, limits the widespread use of this technology in the field[13][14]The development of portable spectrometers could broaden the use of this method in on-site conservation[14].

2.3. Application of BIM technology

BIM, another crucial technology in heritage conservation, has been used to manage the long-term preservation of historical buildings.Fai and Graham argue that BIM facilitates more efficient documentation and helps coordinate conservation activities across large projects[15].Despite its advantages, BIM requires a high level of skill to create accurate models, especially when dealing with irregular or deteriorated structures[15][16].Training programs for heritage professionals could address the skill gap and improve the adoption of BIM technologies in conservation[16].

Recent studies have also emphasized the sustainability of using digital technologies, particularly 3D printing, in heritage conservation.3D printing has been shown to reduce material waste and allows conservators to replicate damaged elements without altering the original structures[17].However, the energy demands of 3D printers are high, and their environmental benefits are currently offset by this significant energy consumption[17][18].Future research could focus on making 3D printing more energy-efficient, reducing its environmental impact while maintaining its conservation benefits[17].

To sum up, advanced technologies such as X-ray spectrometer, point cloud data technology, BIM technology, Jingdiao software, and 3D printing technology play their own unique roles in the protection and utilization of cultural relics, providing multi-form technical support for the inheritance and development of cultural relics, and carrying out certain forms of prevention and control of possible risks in the future, such as data damage, man-made damage to cultural relics, and damage to natural factors.

3. Methods

3.1. Research Philosophy

Three-dimensional scanning technology is currently widely used in the protection of cultural relics, first using X-ray spectrometer to scan cultural relics, uploading data, and secondary processing through software such as point cloud data.X-spectroscopy technology has played an important role in the field of preservation and restoration of cultural relics, and the processing of 3D models is an indispensable link.The Meixian Museum has successfully modeled and restored some of the cultural relics in its collection by using 3D laser scanning technology, outlining a comprehensive and detailed outline for the cultural relics, realizing the all-round collection and collection of cultural relics information, the virtualization and digital construction of exhibitions, and the restoration of cultural relics [19].Three-dimensional data achieves the whole process from collection to analysis, analysis to restoration, restoration to display.

To enable broader use and dissemination of cultural relics, three-dimensional data can be extended to support industrial production and cultural creativity. Taking the construction data of dougong as an example, this process begins with collecting data via X-ray spectrometry, refining the 3D printing master model, enhancing carving software designs, and ultimately producing the final mold. Each stage meets specific goals: X-ray spectrometry for preservation, design refinement for restoration, mold production for industrial-scale replication, and subsequent development for wider dissemination. This seamless process—from data archiving to design, from development to production—offers a new approach to preserving and sharing cultural relics through digital means.

In this era, the future trend driven by "digital +" has become very clear, and it is no longer just a simple "digital +" single industry.Now, "Digital+", a dynamic and innovative development strategy that integrates multiple industries, is rapidly emerging.The specific idea is shown in the figure 1.

3.2. Data module process optimization based on point cloud technology and 3D printing

3.2.1. Point cloud data algorithm processing

The collection and processing of point cloud data play a significant role in the protection and research of historical architectural heritage, typically gathered using laser scanners or 3D acquisition sensors. During data collection and analysis, specific algorithmic formulas are required. The data is then processed through algorithms and translated using BIM software, offering a novel approach to the preservation of historical architectural heritage.

ICP algorithm (Iterative Closest Point) is an important algorithm for point cloud registration.Specifically, it is as follows: Equation (1):

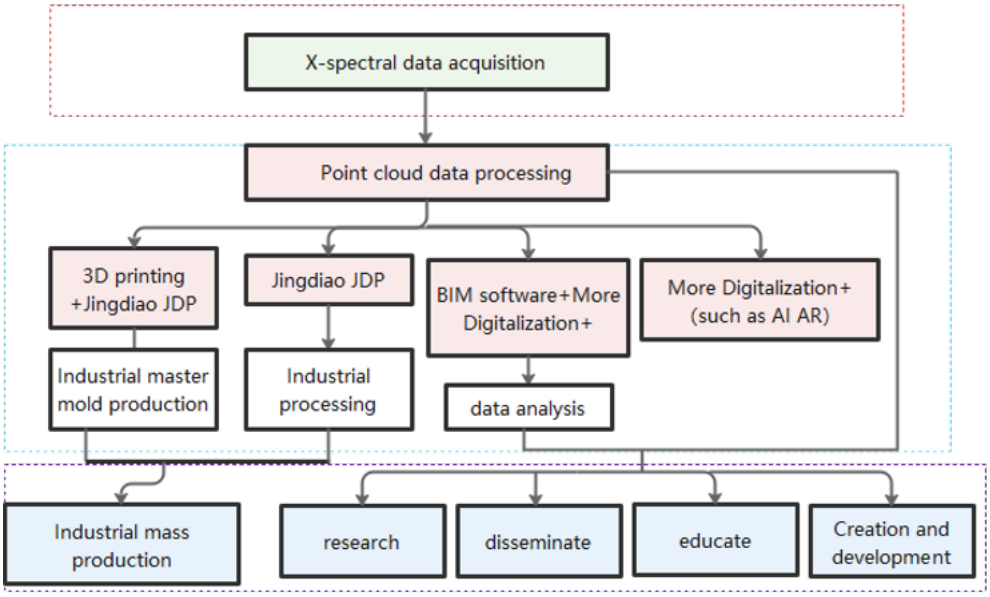

Fig. 1. Conceptual framework

$$R, t = \arg\min_{R,t} \sum_{i=1}^{N} \|Rp_i + t - q_i\| \qquad (1)$$

In the equation, P_i represents the points collected in the source point cloud data, q_i represents the nearest neighboring points in the target point cloud, and R and t represent the rotation matrix and translation vector, respectively. By controlling the change in the calculated quantities, the minimum distance between the point clouds is found, aligning and verifying the source point cloud with the target point cloud.

After data processing, to better integrate with BIM software and establish a link, the point cloud data needs to be segmented.Based on RANSAC (Random Sample Consensus) model fitting, algorithmic analysis is conducted, as shown in the following formula (2):

In the equation, P_i represents the point data in the

$$d(p_i, M) = distance(p_i, M) \leq \epsilon \qquad (2)$$

point cloud, M represents the geometric model, and ϵ epsilonϵ represents the distance threshold.

The BIM + 3D scanning technology model is regarded as the core part of the initial data collection process.By collecting the point cloud data generated from the dougong (traditional Chinese architectural brackets), this data is then converted into LAS format and loaded into BIM software .This enables the linking and analysis of point data.

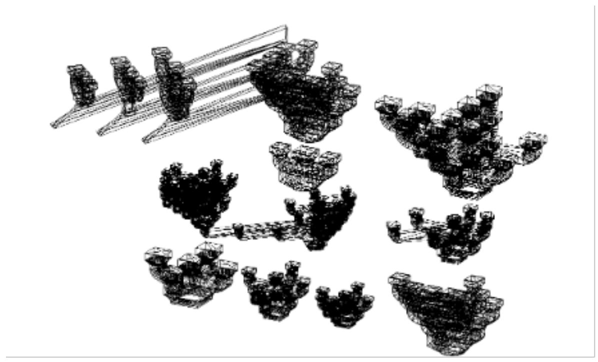

Fig. 1. BIM processing data model

3.2.2. Curve optimization and path processing

The Bezier curve defines a parametric curve through a set of control points, and is an algorithm in computer graphics, 3D modeling, and other fields [20].The curve algorithm is used to control the generation of smooth curves, which restores the original form of the construction and provides a theoretical algorithm basis for restoration and preservation.The parametric equation is described in (3):

In the equation, B(t) represents the parametric form of the Bezier curve, P_i denotes the control

$$B(t) = \sum_{i=0}^{n} B_{i,n}(t) P_i \qquad (3)$$

points, t is the parameter with a range between 0 and 1, and $B_{i,n}(t)$ is the basis function of the Bezier

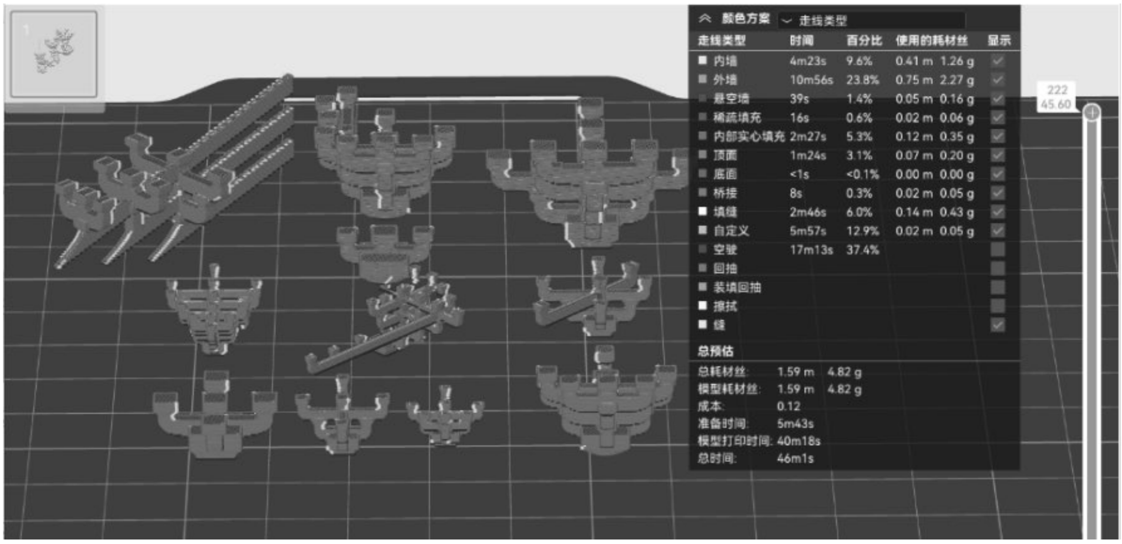

Fig. 2. Preliminary collation analysis of the model

curve, defined as shown in equation (4).In the figure, $\binom{n}{i}$ represents the binomial coefficient:

$$B_{i,n}(t) = \binom{n}{i}(1-t)^{n-i}t^i \tag{4}$$

Using Bezier curves, the planning and calculation of animation and motion trajectories in 3D printing ensure that the generated surface has good smoothness and flatness.This allows each adjacent curved surface to be accurately adjusted and refined.The obtained dougong model data is then reasonably extracted.During the extraction process, the following slicing formula is strictly applied, where N is the total number of layers, H is the total height, and h is the height of each layer, as shown in equation (5):

$$N = \frac{H}{h} \tag{5}$$

During the processing, the 3D model undergoes voxelization, converting the model into a discrete voxel grid, which plays an important role in simulation, rendering, and printing on a computer.This process follows the formula (6):

$$V(x,y,z) = \begin{cases} 1 \ \textit{if } (x,y,z) \textit{ is inside the object} \\ 0 \quad \text{otherwise} \end{cases} \tag{6}$$

In the equation, (x,y,z) represents the coordinates of a voxel in 3D space, while V(x,y,z) determines whether the voxel is inside the target object.If it is inside, V(x,y,z)=1, otherwise it is 0.Voxelization

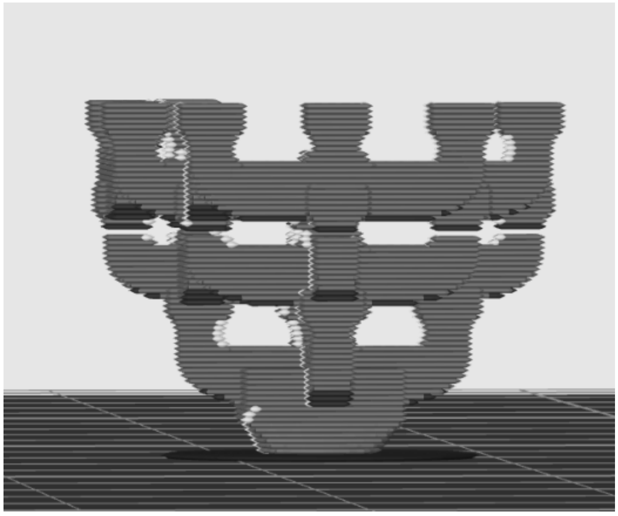

Fig. 3. Slice processing analysis

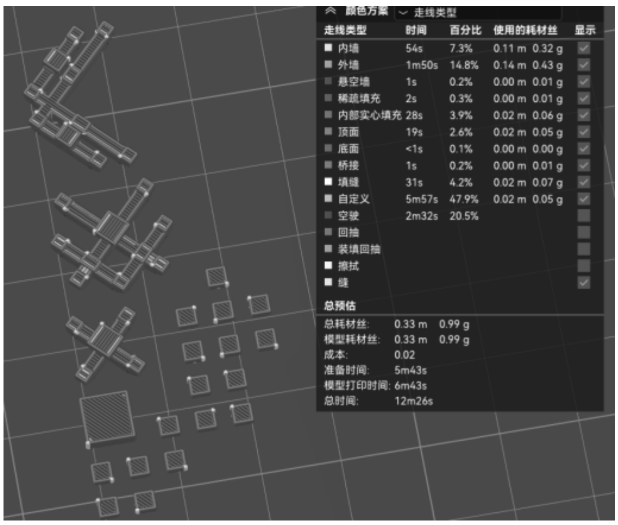

Fig. 4. Module splitting

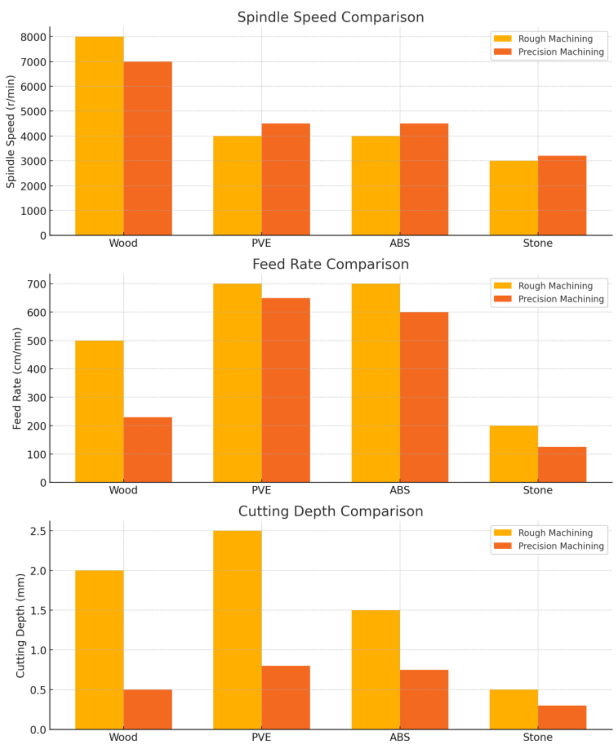

Fig. 5. Histogram comparison

facilitates the segmentation of complex geometric shapes and allows for efficient processing of these shapes。

3.3. Jingdiao JDP fine chemical industrial production

3.3.1. Materials and Processing

In the design and processing of materials such as jade, wood, and PVC, fine carving technology plays an important role in detailed analysis and processing. Depending on the material, spindle speed, feed rate, and other parameters of Jingdiao data vary significantly. For the refinement of the dougong model created through 3D printing, the relevant parameters are presented in the table 1.

3.3.2. Toolpath algorithm

The toolpath is an important parameter that needs to be accurately controlled in Jingdiao software, and the geometric planning of the route restores the authenticity of the original object.There are two modes of linear interpolation and circular interpolation, and circular interpolation is based on linear interpolation, so linear interpolation is the basic form, and its linear interpolation algorithm follows the following formula (7):

where P(t) is the position of the tool at time t, and $P_1$and P_0 are the coordinates of the start and end points, respectively.

$$P(t) = P_0 + t(P_1 - P_0), 0 \le t \le 1 \qquad (7)$$

The algorithm for circular interpolation follows the following equation (8):

where (x_c, y_c) is the coordinate of the center of the circle, r is the radius of the arc, and θ(t) is the

$$P(t) = (x_c + r\cos(\theta(t)), y_c + r\sin(\theta(t))) \qquad (8)$$

angle that changes with time t.

3.3.3. Tool compensation algorithms

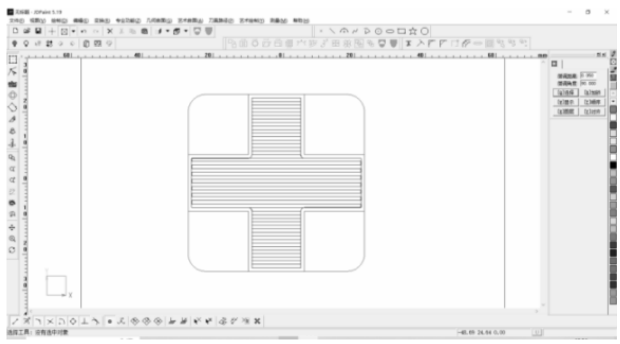

Fig. 6. Contour finishing

Table 1. Finishing parameters for different materials

Material	Flat-bottomed bits (mm)	Rough machining			Fine machining		
		rotate speed (r/min)	Feed rate (cm/min)	The amount of the knife (mm)	rotate speed (r/min)	Feed rate (cm/min)	The amount of the knife (mm)
timber	10	8000	500	2	7000	230	0.5
PVE	2.5	4000	700	2.5	4500	650	0.8
ABS	3	4000	700	1.5	4500	600	0.75
Stone	15	3000	200	0.5	3200	125	0.3

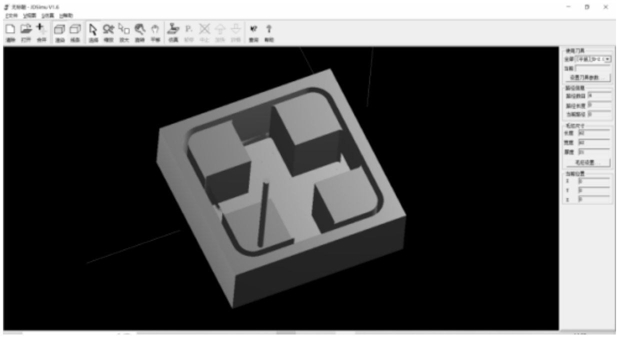

Fig. 7. Zone processing

In the actual machining, due to the shape number and size of the tool, the path trace of the multi-dimensional control does not conform to the walking path of the tool, so in the actual machining process, the physical properties of the tool will cause wear and error, so the tool compensation algorithm is used to correct the error of the tool radius or shape for the machining accuracy.The formula for the tool compensation algorithm is as follows (9):

where $P_{corrected}$ is the corrected path, P_{path} is the

$$P_{corrected}(t) = P_{path}(t) + r\hat{n}(t) \tag{9}$$

original path, r is the tool radius, and $\hat{n}(t)$ is the normal of the path.

3.3.4. Production practices

To verify the feasibility of modular production, this paper focuses on mural sculpture, an integral part of ancient building construction. Using an X-ray spectrometer to scan data for detailed processing, the workflow enables seamless data transfer between carving software, allowing the transformation from original object to model in an industrialized production process. Production trials are conducted on materials with varied properties to test the feasibility and sustainability of digital module production.

4. Results and Discussion

4.1. Strategies for digitizing the module chain

The in-depth exploration of the BIM+3D scanning module chain—from the preliminary design phase of a classical building to the completion of its final restoration—demonstrates the critical role of BIM+3D scanning technology. By utilizing BIM's advanced modeling tools, the collected data can be integrated and transformed into a detailed 3D model. This model clearly displays the various parts and decorations of the ancient building. With the assistance of this model, design experts and cultural heritage conservation staff can perform thorough analysis and develop more accurate, scientifically grounded conservation and restoration plans. For instance, during the restoration of an ancient building, it is crucial to precisely identify the size and shape of the damaged sections, allowing the selection of the most appropriate repair materials and techniques to ensure the restoration closely matches the building's original condition.

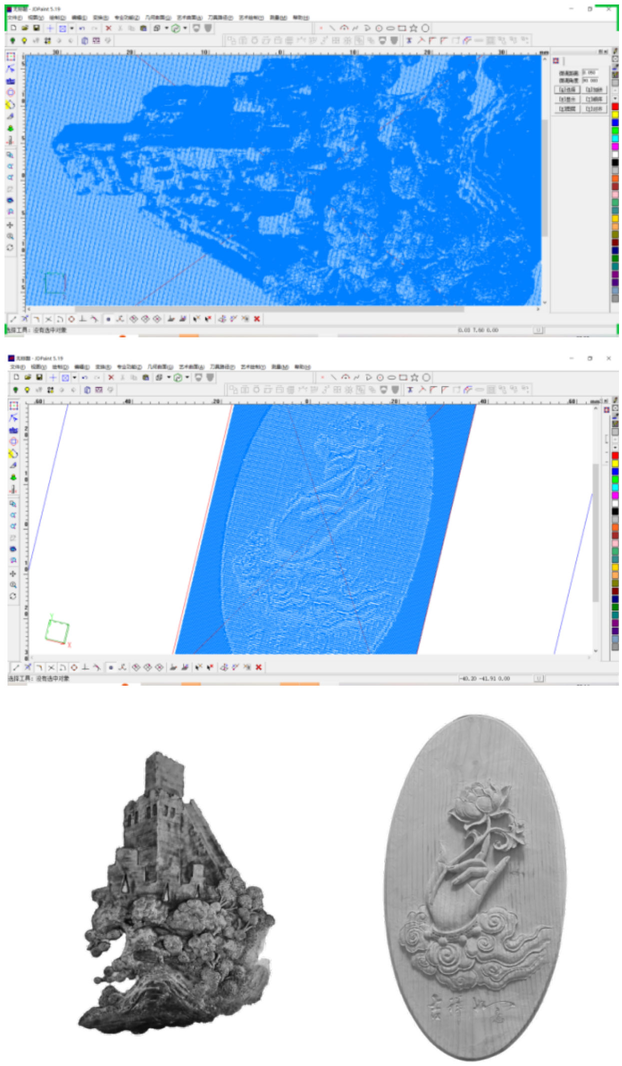

Fig. 8. Production practices

The integration of 3D printing technology with carving techniques offers more flexible possibilities for design approaches. The modularity of 3D printing combined with fine carving technology, which combines the advantages of rapid prototyping and detailed engraving, enables the creation of stunning quality, whether for complex industrial parts or high-end works of art. This not only advances progress in the manufacturing industry but also opens up broader opportunities for artistic creation.

The deep integration of mold-making technology and production methods has significantly improved industrial efficiency. By combining precise mold manufacturing techniques with efficient production processes, both product quality and production efficiency have been successfully enhanced. This integration benefits a wide range of industries, from artifacts to cultural products, driving progress and transformation across sectors.

The development of cultural creativity, when combined with its application in education, creates a strong foundation for both the inheritance and innovation of culture. On one hand, cultural and creative development incorporates cultural elements into various products, allowing culture to enter people's daily lives in a more engaging and enjoyable way. On the other hand, cultural and creative products serve as valuable teaching resources, enabling students to experience the allure of culture during the learning process while fostering their innovative thinking and cultural awareness.

4.2. innovation

This modular approach to thinking is bound to become more widespread in the future, serving as a key driver of social progress. The collaborative integration of multiple industries, fields, and directions will also receive unprecedented attention in terms of cultural dissemination and application. It not only facilitates resource sharing and the mutual enhancement of different industries but also creates a broader platform for the inheritance and innovation of cultural heritage.

The rapid expansion of digital technology will drive the deep integration of product functions, production technologies, business models, and consumption patterns across industries, shaping a new paradigm for industrial integration and development. Over the years, the government has consistently promoted policies supporting multi-industry integration to encourage and facilitate the development of "digital +" multi-industry initiatives. At the same time, as technology continues to evolve, new integration methods and application scenarios will gradually emerge. With the advancement of cutting-edge technologies such as artificial intelligence, big data, and the Internet of Things, broader opportunities for cross-industry integration will arise.

Overall, the multi-industry integrated development module chain of "digital +"—with its strong innovative capacity and vitality—provides a clear direction for future social progress. In this era of diverse opportunities and challenges, cross-industry integration is expected to play an increasingly critical role in the transmission and practice of culture, which represents its future development trend.

5. Conclusion

Thanks to the continuous advancement of digital software technology and the ongoing updates in scanning technology, the restoration, conservation, research, and development of cultural relics have been significantly accelerated. When working with a variety of complex data software, there is a tendency to modularize and consolidate numerous requirements. By adopting advanced sculpting and model-making technology that combines scanning with 3D printing, modular chain technology not only meets the needs of production activities but also adapts to the ongoing development trends of modern society. For cultural heritage to be more widely disseminated, the digital representation of cultural relics must be adjusted to transform objects that would otherwise be difficult to understand into easily comprehensible forms. Due to the diversity of design forms, the digital resources of cultural relics are more accessible during the process of sharing and dissemination, and can also meet the multiple needs of industrial manufacturing and media. This modular approach plays a decisive role in both preserving culture and ensuring its continuous progress.

With the introduction of national policies promoting the implementation of digital cultural technology, the development of the "digital +" model has become inevitable. This modular chain approach aligns with the mainstream development direction for the future and holds significant social, economic, and cultural value. The future of "digital +" will no longer be limited to a single industry, but will give rise to a "digital +" multi-industry integration model. Technologies such as BIM combined with 3D scanning, 3D printing coupled with carving, mold-making integrated with production modes, and cultural and creative development combined with teaching applications will play key roles. This modular chain concept will become increasingly popular in the future, with a focus on the dissemination and application of culture through multi-industry, multi-field, and multi-faceted collaboration and integration. Moving forward, the development of this digital technology module chain will continue to evolve, playing an even greater role in the transmission of culture.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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References

1. Zhang, Y.(2019).Digital transformation of cultural heritage protection in China: Applications and challenges of virtual reality technology.Journal of Cultural Heritage, 36, 123–134.https://doi.org/10.1016/j.culher.2019.05.002
2. Li, W.(2018).Application of digital technology in the protection of architectural heritage in China: Case studies and future perspectives.International Journal of Heritage Studies, 24(4), 423–439.https://doi.org/10.1080/13527258.2017.1417284
3. Tian, J., Wu, C., Zhao, Y., & Wu, L.(2022).Application of 3D printing technology in cultural heritage restoration: A feasibility study.Journal of Cultural Heritage Management and Sustainable Development, 12(3), 415–432.https://doi.org/10.1108/JCHMSD-01-2021-0004
4. Kantaros, A., & Ganetsos, T.(2023).The potential of 3D scanning and 3D printing in cultural heritage: Technological challenges and opportunities.Applied Sciences, 13(8), 4777.https://doi.org/10.3390/app13084777
5. Xu, Y., et al.(2021).Development of policies and legislative framework for the protection of intangible cultural heritage in China.Journal of Cultural Heritage, 46, 127–136.https://doi.org/10.1016/j.culher.2020.12.005
6. Ioannides M, Magnenat-Thalmann N.3D Digitization of Cultural Heritage.In: Ioannides M, Magnenat-Thalmann N, editors.Handbook of Research on 3D Digitization of Cultural Heritage.IGI Global; 2014.p.19–38.https://doi.org/10.4018/978-1-4666-6114-1.ch002
7. Costantino D, Herban S.From 3D Point Cloud to Intelligent Model Set for Cultural Heritage Conservation.Journal of Cultural Heritage.2024;15(2):97–112.https://doi.org/10.1016/j.culher.2024.05.003
8. Karasaka L, Ulutas N.Point Cloud-Based Historical Building Information Modeling (H-BIM) in Urban Heritage Documentation Studies.International Journal of Architectural Heritage.2023;17(4):456–472.https://doi.org/10.1080/15583058.2023.1205823
9. Milosz M, Kęsik J.Challenges and Current Applications of 3D Information Technologies for Cultural Heritage.Journal of Computing and Cultural Heritage.2024;12(1):145–161.https://doi.org/10.1145/3584739
10. Prieto T, Kumar M.The Potential of 3D Printing in Building Pathology: Rehabilitation of Cultural Heritage.Building Research & Information.2020;48(3):284–297.https://doi.org/10.1080/09613218.2020.1692823
11. Moropoulou A, Avramidis A, Zafeiropoulou T, et al.Application of Digital Techniques in Industrial Heritage Areas.Journal of Cultural Heritage.2013;14(3):345–355.https://doi.org/10.1016/j.culher.2013.03.007
12. Milosz M, Kęsik J.3D Printing and X-ray Spectroscopy for Cultural Heritage.Journal of Cultural Heritage Management and Sustainable Development.2024;10(4):215–230.https://doi.org/10.1108/JCHMSD-2023-0046
13. Creaform.Preserving Historical Buildings Using 3D Scanning.Cultural Heritage Preservation Review.2021;23(5):61–75.https://doi.org/10.1007/s10518-021-01044-7
14. Creaform.3D Scanning in the Renovation of Cultural Heritage Sites.Journal of Conservation Science.2021;41(2):138–152.https://doi.org/10.12671/JCS.2021.41.2.12
15. Fai D, Graham R.Building Information Modeling for Cultural Heritage.Journal of Information Technology in Construction.2018;23(1):69–88.https://doi.org/10.1002/itcon.1053
16. Herban S, Costantino D.Building Information Modeling for Heritage Conservation.Heritage Science.2024;16(2):178–192.https://doi.org/10.1186/s40494-024-00742-2
17. Milosz M, Kęsik J.Sustainable Approaches to Cultural Heritage Using 3D Printing.Sustainability.2024;16(1):61–80.https://doi.org/10.3390/su16010051
18. Creaform.Using 3D Models for Historical Building Restoration.Journal of Architectural Heritage.2021;27(4):195–208.https://doi.org/10.1080/15583058.2021.110582
19. Han, H.(2024).Application of 3D scanning technology in cultural relic protection: A case study of Meixian Museum.Journal of Cultural Relic Identification and Appreciation, (15), 41–44.https://doi.org/10.20005/j.cnki.issn.1674-8697.2024.15.011
20. Piegl, L., & Tiller, W.(1997).The NURBS Book.Berlin: Springer.https://doi.org/10.1007/978-3-642-59223-2

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Enhancing Urban Riverside Greenways through Post-Occupancy Evaluation: A Case Study of the Yangtze River Greenway in Wuhan

Keyu Yao [a], Feng Zhou [a], Ran Peng [a,*], Tong Li [a], Jie Ma [a]

[a] *School of Civil Engineering and Architecture, Wuhan Institute of Technology, Wuhan 430074, China*

KEYWORDS

post-occupancy evaluation,
urban riverside greenway,
optimized strategy,
wuhan,
yangtze river

ABSTRACT

In today's commitment to achieving the goal of double carbon and advocating low-carbon life, the riverside greenway, as an important ecological public space in the urban center, plays an important role in improving the quality of life of residents, optimizing the urban transportation structure, restoring the water environment ecology, and further building a low-carbon city. Based on the post-occupancy evaluation of the built environment, this paper takes the Wuchang Greenway, Qingshan Greenway and Hongshan Greenway on the Yangtze River in Wuhan as the research objects, comprehensively evaluates the built environment of the three greenways from the aspects of user behavior characteristics and post-use satisfaction, compares and analyzes the advantages and shortcomings of the three greenways according to the evaluation results, and proposes some optimization strategies for the design of urban riverside greenways.

1. Introduction

1.1. Research Background

The construction of ecological civilization has promoted the development of ecological value theory, prompting a significant change in people's ideological concepts from conquering nature to harmonious coexistence between man and nature [1]. During the "14th Five-Year Plan" period, China's ecological civilization construction has entered a key period focusing on decarbonization, aiming to achieve a qualitative change in the improvement of ecological environment quality from quantitative change to qualitative leap, thus proposing the "dual carbon" strategy of striving to reach peak carbon dioxide emissions before 2030 and striving to achieve carbon neutrality before 2060 [2]. Under the "dual carbon" background, it is particularly important to build a public space that is harmonious and integrated with nature. Many scholars have conducted relevant researches, such as Liu Yueqin and Lin Xuanquan exploring how to create a scientific urban waterfront greenway to achieve a balance between public recreation and ecological sustainable development[3]; Zhang Dou pointed out the functions of waterfront trails in revitalizing urban areas, restoring ecological functions, and highlighting cultural heritage with the example of the waterfront area renewal and reconstruction plan made by Sasaki Company for Lujiazui[4]; Liu Shengwei, Ding Rong, and others summarized the role of urban greenways in regional urban development and thought and explored the practical direction of greenways in future urban renewal[5]. Based on the above, urban waterfront greenways, as linear open

* Corresponding author at: School of Civil Engineering and Architecture, Wuhan Institute of Technology, Wuhan 430074, China.
E-mail address: pengran@wit.edu.cn (Ran Peng)

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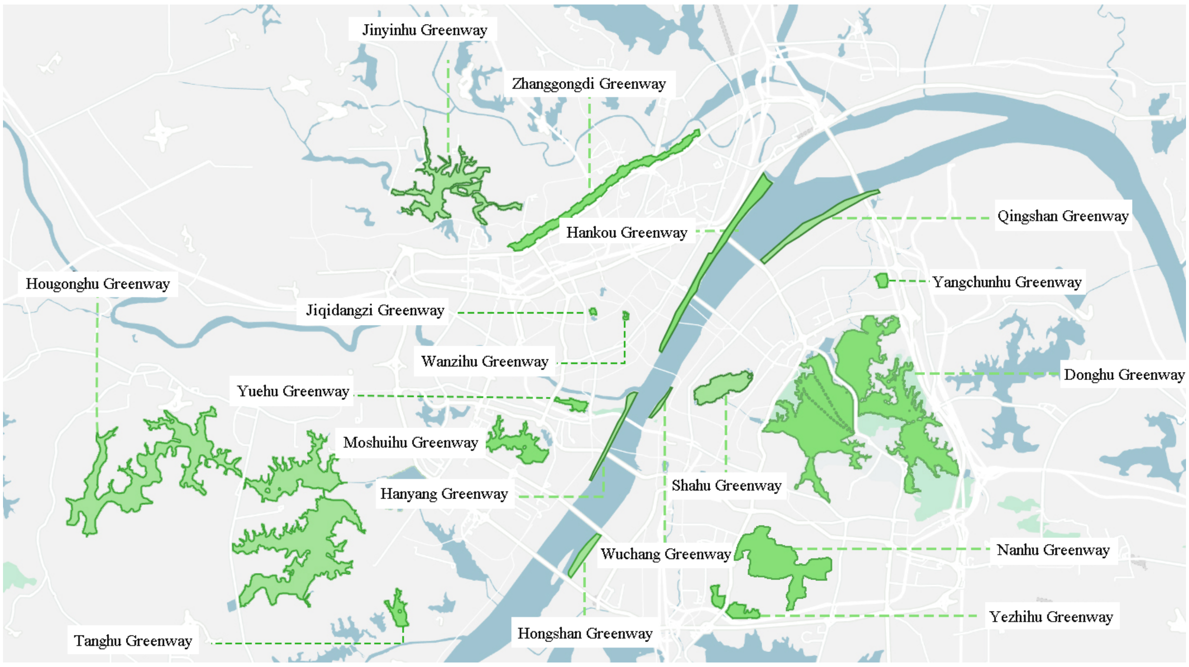

Fig. 1 Distribution of Wuhan's Riverside Greenways

spaces integrating ecological, recreational, social, and economic functions, have a great impact on improving environmental quality, optimizing urban traffic structure, and enhancing the integrity of urban space. Therefore, high-quality urban greenways require specific and effective evaluation, and based on this, more reasonable optimization suggestions can be put forward.

The most common and scientific method for evaluating the built environment of public space in China is the post-occupancy evaluation. In this regard, Liang Chen and Zeng Jian used environmental psychology to conduct post-occupancy evaluations on three waterfront spaces in Tianjin, and found problems in the aspects of activities and facilities[6]; Dong Baoying and others conducted post-occupancy evaluations on Xuanwu Lake Park in Nanjing, summarized the factors affecting the quality of use of urban park water space, and proposed corresponding optimization strategies[7]. Based on this, this paper adopts post-occupancy evaluation as the research method, takes the Yangtze River greenway in Wuhan as an example for investigation and analysis, explores the common problems in the current construction of urban riverside greenways, and provides corresponding optimization strategies for decision-making reference for management departments.

1.2. Research Objects and Methods

1.2.1. Research Objects

Wuhan is an important riverside city, but with the acceleration of urbanization in the Yangtze River Basin, the continuous increase of urban development area, and the beginning of environmental problems such as decreased connectivity, shrinking wetland area, eutrophication of lakes, and high intensity of shoreline development[8]. Therefore, comprehensively improving and repairing the ecological environment of the Yangtze River Basin has become an indispensable task. The planning and construction of urban riverside greenways play an important role in improving the ecological environment of the Yangtze River. Since Wuhan officially started the construction of greenways in 2012, more than 2000 km of various types of greenways have been planned and constructed within ten years (Fig. 1). Among them, the planning and construction of the "Hundred-Mile Yangtze River Ecological Corridor" is the most eye-catching, and the construction of Hankou Greenway, Hanyang Greenway, Wuchang Greenway, Qingshan Greenway, and Hongshan Greenway has been completed, and future transformation and construction will continue, with the goal of achieving a hundred-mile riverside greenway shoreline connection by 2025.

This study selects the Qingshan, Wuchang, and Hongshan riverside greenways on the east side of the Yangtze River in Wuhan for the study, and evaluates the use and satisfaction of the three greenways. The research section is located within the third ring road of Wuhan, where the location is superior, transportation is convenient, the scenery is beautiful, and the coast has commercial, cultural, and educational functions, which is the face of Wuhan, and at the same time, the population flow is large, and the composition of the crowd is rich, which is convenient for the survey, and the obtained data is more representative.

1.2.2. Research Methods

The study first conducted on-site measurements of the three selected riverside greenways, and at the same time, questionnaires were issued to the users of the three greenways to determine the users' satisfaction with each indicator in the evaluation system. Finally, combinations of qualitative and quantitative analysis methods were used to compare and analyze the current use of the three greenways, and then summarize the advantages and disadvantages of the current riverside greenway construction and propose some optimization suggestions.

2. Construction of Wuhan Riverside Greenway Use Evaluation System

2.1. Construction of POE Evaluation System

2.1.1. Selection of Indicators

This paper combines AHP and SD methods for the evaluation of the use of riverside greenways, with the use of riverside greenways as the target layer, and the location conditions, slow traffic system, landscape system, service system, and functional facility system as the criteria layer. It summarizes and screens the adjective pairs used in related research at home and abroad using the SD method, and finally selects 24 indicators and corresponding adjective pairs as shown in Table 1.[9–11].

Table 1. Evaluation Indicators - Hierarchical Model

Target Layer	Criteria Layer	Factor Layer	Adjective Group
City Riverside Greenway Use Situation Evaluation	Location Condition	Accessibility	Accessible-Inaccessible
		Prosperity	Remote-Prosperous
		Transport Convenience	Inconvenient-Convenient
		Parking Lot	Scarce-Abundant
	Slow Traffic System	Road Width	Narrow-Wide
		Environmental Hygiene	Messy-Neat
		Node Continuity	Broken-Continuous
		Node Interest	Boring-Interesting
		Historical and Cultural Value	Low-High
		Safety	Dangerous-Safe
	Landscape System	Landscape Diversity	Scarce-Rich
		Plant Coverage Rate	Low-High
		Aquaticity	Close-Distant
		Water Quality	Poor-Good
	Service System	Sales Station	Scarce-Abundant
		Public Toilet	Scarce-Abundant
		Service Point	Scarce-Abundant
		Trash Can	Scarce-Abundant
		Visibility	Hidden - Obvious
	Functional Facility System	Rest Facilities	Scarce-Abundant
		Lighting Facilities	Dim-Bright
		Signage	Poor-Good
		Diversity	Single-Diverse
		Aesthetics	Ugly-Beautiful

2.2. Calculation and Analysis of Weights

Considering the large amount of calculation in the Analytic Hierarchy Process (AHP), this paper uses the AHP calculation software yaahp to build a hierarchical model, input the expert's assignment values for the evaluation indicators into the software to generate a judgment matrix, and then adjust the data with inconsistencies to finally obtain the weights of each evaluation indicator and the consistency check results (Table 2).

The complete process for calculating and testing the weights of indicators is as follows:

a. Construct the Judgment Matrix: Use the matrix scaling method to quantitatively assign values to the evaluation factors in the constructed hierarchical analysis model according to data collection, expert opinions, and the experience of scientific researchers to obtain the corresponding judgment matrix.
b. Calculate the Weights of Each Indicator: Use formula (1) to calculate the weight value Wi for each evaluation factor.
c. Conduct Consistency Check on the Judgment Matrix: First, use formula (2) to calculate the Consistency Index C.I (denoted as σ(C.I) in the formula), and according to formula (3), the ratio of the C.I value obtained in formula (2) to the average random consistency index R.I (denoted as σ(R.I) in the formula) of the same order is called the upper-level consistency ratio C.R (denoted as σ(C.R) in the formula). When σ(C.R) < 0.1, it is considered that the consistency of the judgment matrix is acceptable, and the calculation result is reasonable and effective; otherwise, the judgment matrix needs to be corrected[12].

$$W_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{ij}} \quad (1)$$

$$\lambda_{max} = \frac{1}{n}\sum_{i}\frac{(AW)_i}{W_i} \quad (2)$$

$$\sigma(C.I) = \frac{\lambda_{\max} - n}{n-1} \quad (3)$$

$$\sigma(\mathrm{C.R}) = \frac{\sigma(\mathrm{C.I})}{\sigma(\mathrm{R.I})} \quad (4)$$

Table 2. Weight Values and Consistency Check Values of Each Factor Layer of Riverside Greenway

Criteria Layer	Factor Layer	Factor Weight Wi Value	Consistency Check C.I Value
Location Conditions	Accessibility	0.4445	0.0267＜0.1
	Prosperity	0.2832	
	Transport Convenience	0.1072	
	Parking Lot	0.1651	
Slow Traffic System	Road Width	0.1753	0.0480＜0.1
	Environmental Hygiene	0.1920	
	Node Continuity	0.1141	
	Node Interest	0.1421	
	Historical and Cultural Value	0.1026	
	Safety	0.2739	
Landscape System	Landscape Diversity	0.1397	0.0456＜0.1
	Plant Coverage Rate	0.2748	
	Aquaticity	0.1981	
	Water Quality	0.3873	
Service System	Sales Station	0.1078	0.0441＜0.1
	Public Toilet	0.2490	
	Service Point	0.1705	
	Trash Can	0.1929	
	Visibility	0.2798	
Functional Facility System	Rest Facilities	0.2838	0.0482＜0.1
	Lighting Facilities	0.2508	
	Signage	0.1419	
	Diversity	0.2171	
	Aesthetics	0.1063	

Fig. 2 Location Map of Wuchang, Qingshan, and Hongshan Riverside Greenways in Wuhan

It can be seen from Table 2. that among the 24 selected indicators, the top 5 in weight ratio are safety, accessibility, environmental hygiene, trash cans, and road width. This indicates that the people-oriented design concept is a consensus, and the design of riverside greenways needs to meet the requirements of safety, accessibility, and comfort.

3. Wuhan Riverside Greenway Location Conditions and Spatial Features

3.1. "Lungs of the City" - Ribbon Park Built Along the River

3.1.1. Basic Overview of Wuhan Riverside Greenway

This paper selects the Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway of Wuhan as the research subjects, which are important riverside ecological parks in Wuhan (Fig. 2). Among them, the Hongshan Greenway (from Yangsi Port Bridge to Baishazhou Bridge section) is a total length of 3120m and is an important node project of Wuhan's hundred-mile ecological and cultural corridor[13]. The Wuchang Greenway (between the Yangtze River Bridge and the Yangtze River Tunnel) is a total length of 1200m and is one of the earliest constructed sections of the Wuchang Greenway. The Qingshan Greenway (from Erqi Bridge to Tianxingzhou Bridge section) is a total length of 7500m. As a part of the main axis of the Yangtze River, it is the first "river, beach, city" three-in-one ecological greenway in Wuhan, the first "sponge" greenway in Hubei Province, and also the greenway with the highest greening ratio.

3.1.2. Surrounding Entertainment and Commerce

With the center of Hongshan Greenway as the center, there are no large commercial areas within a 1.5 km radius, and the area south of the greenway is mostly residential (Fig. 3). With the center of Wuchang Greenway as the center, there are no large commercial areas within a 1.5 km radius, and the area south of the greenway is mostly residential. There are tourist attractions such as Tanhualin, Hubuxiang, and the Revolutionary Museum around (Fig. 4). With the center of Qingshan Greenway as the center, there are two medium-sized commercial areas within a 1.5 km radius, and the area south of the greenway is mostly residential (Fig. 5).

3.1.3. Traffic Analysis

The public transportation of Hongshan Greenway mainly relies on Metro Line 11 (under construction), with 8-11 bus stations within 1 km of each entrance and exit (only two open entrances are recorded). The public transportation of Wuchang Greenway mainly relies on Metro Lines 2 and 5, with 5-19 bus station stops within 1 km of each entrance and exit. The public transportation of Qingshan Greenway mainly relies on Metro Line 5, with 10-21 bus station stops within 1 km of each en-

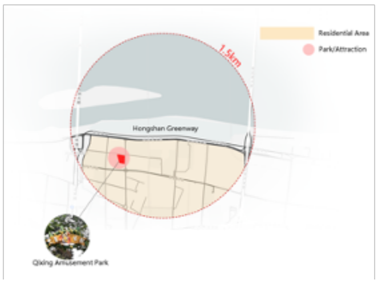

Fig. 3. Distribution Map of Entertainment and Commerce around Hongshan Greenway

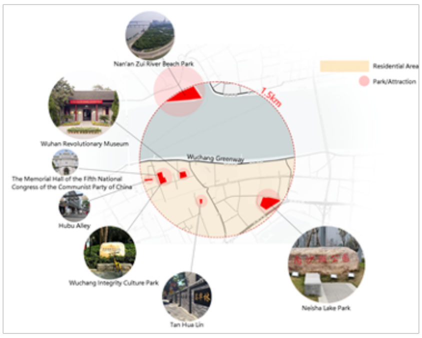

Fig. 4. Distribution Map of Entertainment and Commerce around Wuchang Greenway

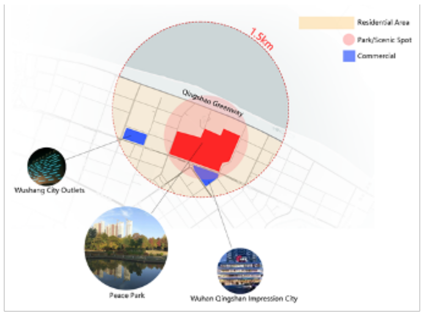

Fig. 5. Distribution Map of Entertainment and Commerce around Qingshan Greenway

trance and exit. Through the comparison in Table 3., it can be found that the convenience of Wuchang Greenway is higher than that of Qingshan Greenway, and Hongshan Greenway has the lowest.

3.2. *"Quiet in the Bustle" - Linear Space under the Bustling City*

3.2.1. *"Three Zones and Three Belts" Features*

In the long-axis direction, it consists of the sightseeing tour area, central square area, and leisure activity area, which are interconnected by landscape nodes. In the short-axis direction, it consists of the embankment viewing belt, leisure shade belt, and riverside feature belt, forming the "three belts"[9]. The embankment viewing belt is mainly planted with low shrubs, with some areas planted with trees; the leisure shade belt has a variety of plant types and is the area with the highest vegetation coverage, with Tingbu, small gravel paths, and trails as the traffic skeleton, connecting landscape, leisure and entertainment areas, and characteristic sculpture artworks, rest facilities; the riverside feature belt integrates high-platform viewing, platform

Table 3. Statistical Table of Public Transportation Station Information near Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway

Entrance		Distance to the Nearest Subway Station (m)	Number of Subway Stations within 1.5km	Distance to the Nearest Bus Station (m)	Number of Bus Stations within 1km
Hongshan Greenway	Gate 1	1300 (under construction)	1 (under construction)	148	8
	Gate 2 (not open)	/	/	/	/
	Gate 3 (not open)	/	/	/	/
	Gate 4 (not open)	/	/	/	/
	Gate 5 (not open)	/	/	/	/
	Gate 6	1100 (under construction))	2 (under construction)	412	11
Wuchang Greenway	Main Entrance	575	3	111	18
	Gate 2	561	3	305	18
	Gate 3	542	3	587	5
	Gate 4	343	5	192	19
Qingshan Greenway	South Gate 1	1300	1	226	14
	South Gate 2	1300	2	239	10
	South Gate 3	950	1	142	19
	South Gate 4	904	1	87	21
	South Gate 5	1200	2	135	15
	South Gate 6	1100	1	120	15
	South Gate 7	995	1	120	14
	South Gate 8	1000	2	151	14
	South Gate 9	1100	2	365	18

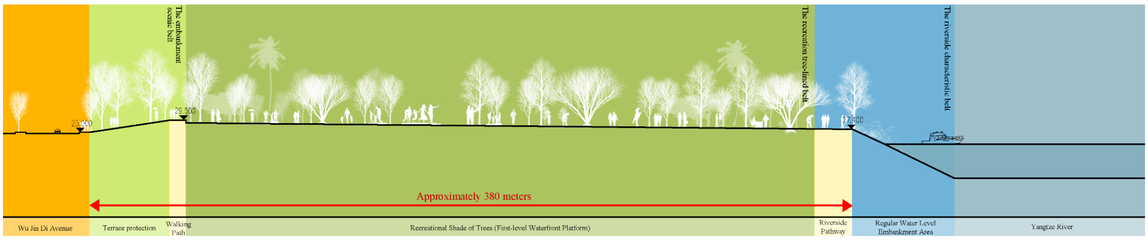

Fig. 6. Cross-sectional Analysis of Hongshan Greenway

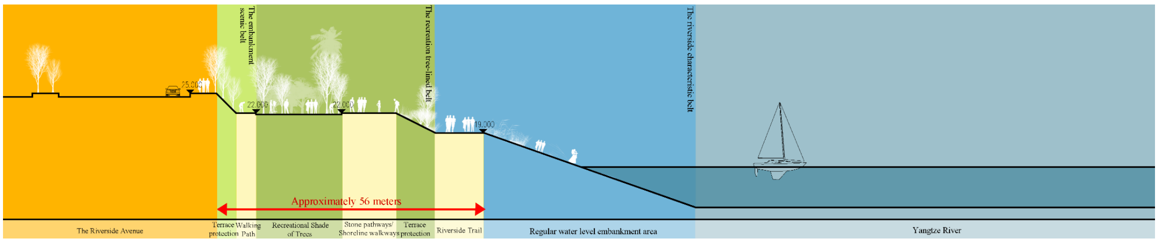

Fig. 7. Cross-sectional Analysis of Wuchang Greenway

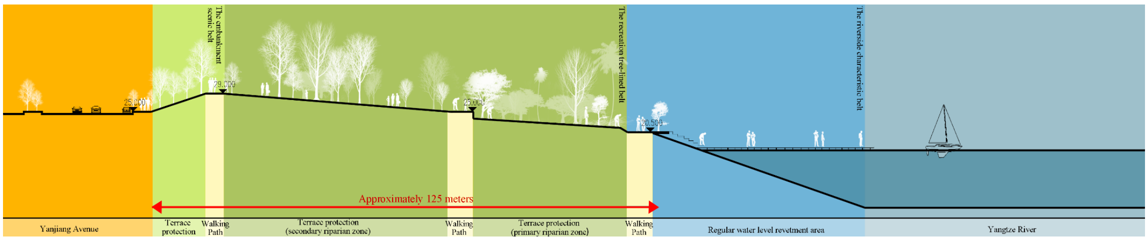

Fig. 8. Cross-sectional Analysis of Qingshan Greenway

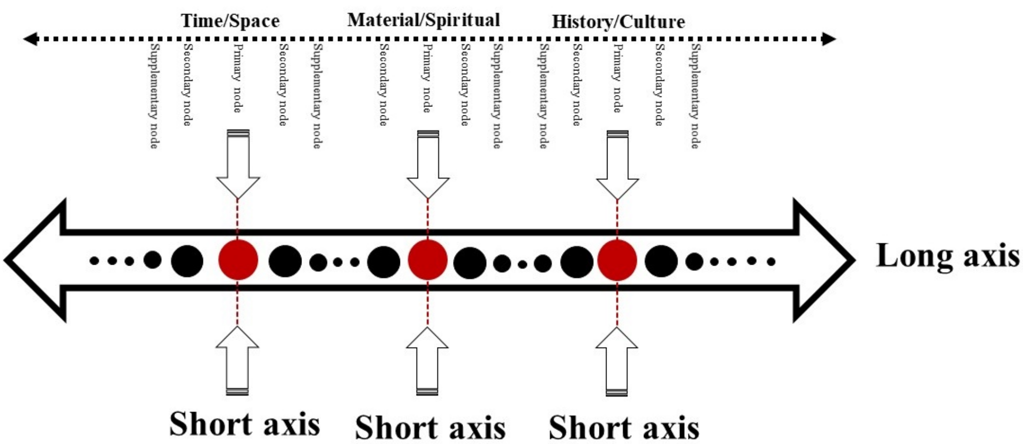

Fig. 9. Spatial Sequence of Ribbon Park

river viewing, and terrace water play, and is equipped with rest facilities along the way.

The overall pattern of the riverside greenway is "three zones and three belts". Wuchang Greenway has a short depth, steep slope, and fewer types of leisure compared to the other two greenways; Hongshan Greenway and Qingshan Greenway have a long depth and gentle slope, with ample space between the riverside trail and the street-side viewing trail to plant multi-level plants and set up a variety of leisure types (Fig. 6-8).

3.2.2. Linear Space Dominated by Square Nodes

In terms of spatial form, the riverside greenway is a linear space with a certain width, which is different from point-shaped and surface-shaped green spaces, and has continuous characteristics[14]. The three greenways all arrange the main nodes in the

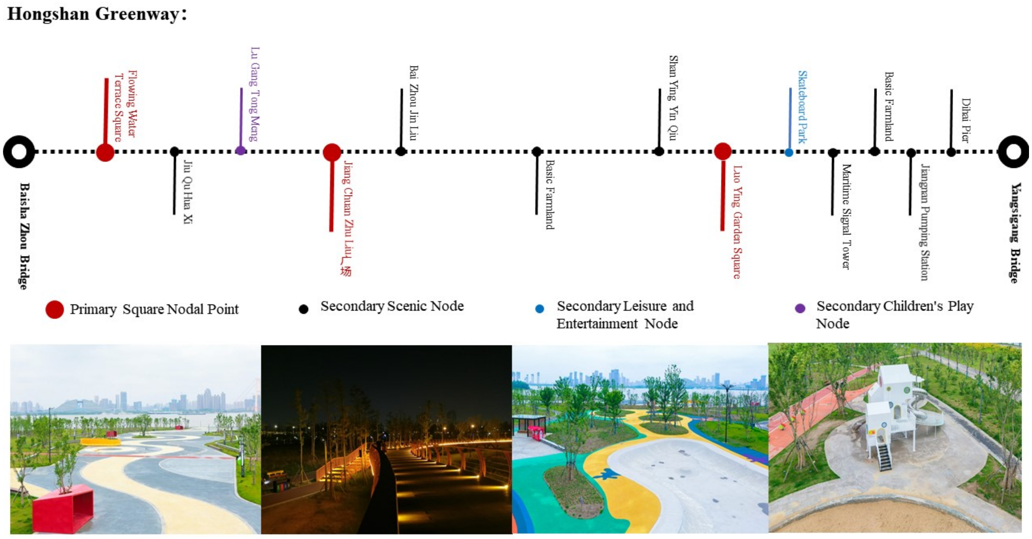

Fig. 10. Distribution Map of Nodes in Hongshan Greenway

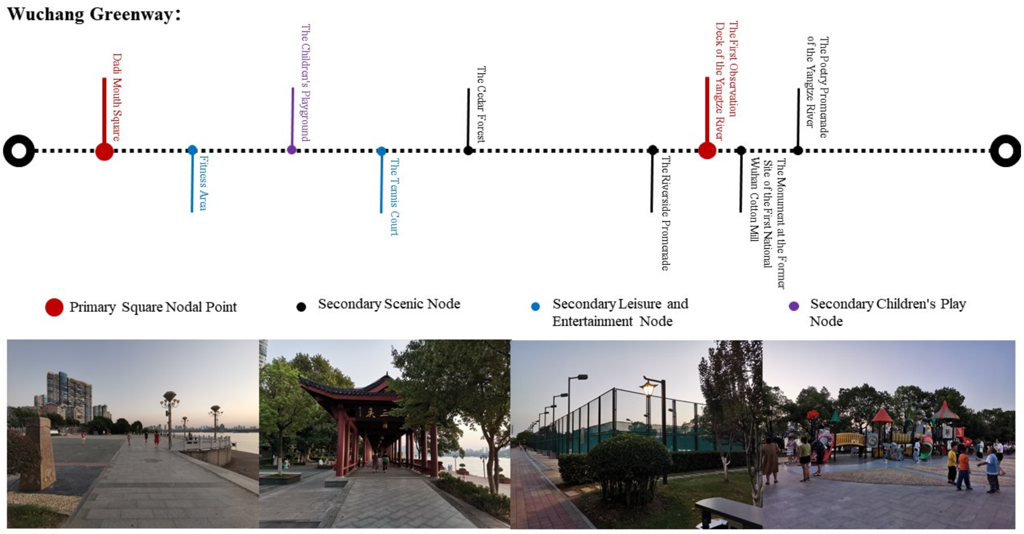

Fig. 11. Distribution Map of Nodes in Wuchang Greenway

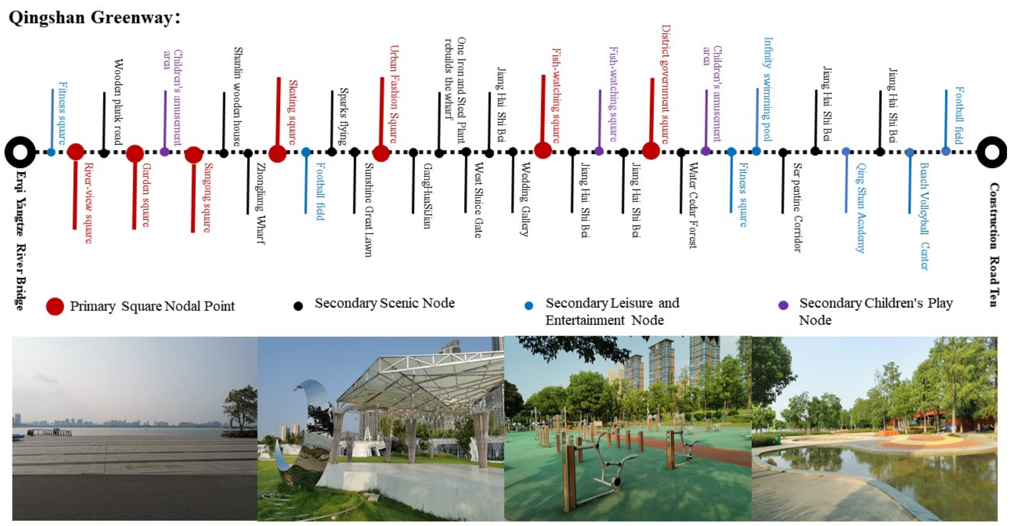

Fig. 12. Distribution Map of Nodes in Qingshan Greenway

long-axis direction, forming a spatial sequence dominated by square nodes, with landscape nodes, leisure and entertainment nodes, and children's play nodes as the second, and other supplementary nodes as the auxiliary (Fig. 9).

3.2.2.1. *Diversified Node Types*

Through field research, the nodes of the three riverside greenways are divided into four categories: square nodes, landscape nodes, leisure and entertainment nodes, and children's play nodes (Fig. 10-12). Among them, square nodes are often associated with entrances and exits, stations, public toilets, and other spaces, with large space and high passenger flow; landscape nodes add richness to the leisure route by combining cultural characteristics, setting landscape artworks, preserving historical docks and sluices, and special plant shapes; leisure and entertainment nodes include fitness squares, roller skating rinks, swimming pools, football fields, and other leisure and fitness venues, providing social space and enhancing physical fitness; children's play nodes are specially designed for children's play areas, stimulating the vitality of the park.

3.2.2.2. *Continuous Spatial Sequence*

The density of nodes and the way nodes transition will affect the formation of a continuous spatial sequence. Through the comparison in Table 4., it can be found that the node layout of Wuchang Greenway is relatively dense, with an average of one node every 133 meters. The node spacing of Hongshan Greenway is relatively far, about 238 meters. Overall, the proportion of landscape nodes is the highest, the proportion of children's play nodes is the lowest, and the proportion of square nodes is relatively average, around 21%. Among them, the proportion of landscape nodes in Hongshan Greenway is much higher than in the other two greenways, while the proportion of leisure and entertainment nodes is much lower than in the other two greenways, indicating that Hongshan Greenway focuses on landscape creation but neglects people's leisure and entertainment activities.

4. Current Survey of Wuhan Riverside Greenway

4.1. Slow Traffic System

The slow traffic system in the riverside greenway mainly includes pedestrian systems and sightseeing

Table 4. Node Statistics Table of Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway

	Hongshan Greenway	Wuchang Greenway	Qingshan Greenway
Square Nodes	23.3%	22.2%	21.2%
Landscape Nodes	61.5%	44.4%	48.5%
Leisure and Entertainment Nodes	7.6%	22.2%	21.2%
Children's Play Nodes	7.6%	11.2%	9.1%
Total Number of Nodes	13	9	33
Node Spacing	About 238m	About 133m	About 227m

Table 5. Current Status of Green and Recreation System in Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway

	Hongshan Greenway	Wuchang Greenway	Qingshan Greenway
Width of Leisure Shade Belt	245m	33m	89m
Rest Areas	Set along the landscape road, with a larger number	Set along the landscape road, with a smaller number	Set along the landscape road, with a spacing of about meters, with a larger number
Children's Play Areas	1	1	3
Plant Richness	Mainly shrubs, average plant richness		
Plant Neatness	Plant neatness is poor, with many areas lacking planning and trimming	Plant neatness is average, with dedicated staff for plant trimming	Plant neatness is good, with dedicated staff for plant trimming

car tour routes. There is no dedicated bicycle lane set up inside the greenway, and motor vehicles and non-motor vehicles are prohibited. The pedestrian system mainly includes embankment viewing trails, middle section leisure paths, and riverside trails, with sidewalk widths ranging from 2-6 meters. It can be seen from Figures 13-15 that Qingshan Greenway has the greatest number of trails, Wuchang Greenway has the fewest curves; Qingshan and Hongshan Greenways mainly feature winding and varied trails, yet daytime utilization is low due to insufficient shade. Wuchang Greenway opts for straight, direct sidewalks, resulting in high utilization.

4.2. Green and Recreation System

The current construction of the green and recreation system in Hongshan, Wuchang, and Qingshan greenways is shown in Table 5.

According to relevant information, when the width of the riverbank vegetation is greater than 30m, it can effectively reduce temperature, increase the supply of food for river organisms, and effectively filter pollutants. When the width is greater than 80-100m, it can better control sediment and soil element loss[10]. The widths of the riverbank vegetation in Hongshan, Wuchang, and Qingshan greenways are all greater than 30m, and the width of the riverbank vegetation in Hongshan Greenway is over 100m, with the best ecological regulation effect.

Overall, the green and recreation systems of the three greenways need to be further integrated and improved, with increased plant richness and enhanced maintenance and renewal of plants in the later period.

4.3. Service System

The greenway service system covers public service facilities, sales stations, public toilets, parking lots, etc. In the construction of greenways, the perfection of service facilities can bring a good experience to visitors[10]. The current construction of the service system in Hongshan, Wuchang, and Qingshan greenways is shown in Table 6.

Overall, the service facilities of the three greenways are inadequate, with existing facilities in small numbers, insufficient to meet user needs. It is essential to establish tourist information centers and medical first aid stations, as well as to incorporate sales kiosks or vending machines.

4.4. Greenway Signage System

The urban greenway signage system consists of signage carrier facilities and signs. The signage carrier facilities are composed of information walls, information strips, and information blocks, and the signs include seven categories: facility signs, directional signs, regulatory signs, warning signs, activity signs, safety signs, and educational signs[10]. The signage systems in Hongshan, Wuchang, and Qingshan greenways are relatively comprehensive, generally set at road forks or nodes, with obvious positions and clear and easy-to-understand signs. They basically meet the requirements.

4.5. Greenway Lighting System

The lighting system in the park greenway generally refers to the road lighting facilities and landscape lighting facilities at night. Through the application of lighting, it emphasizes the greenway axis, and enhances the ornamentality and characteristics of the signs, places, and special landscape nodes[10]. Hongshan Greenway mainly uses road lighting facilities along the way, and also has ground light

Table 6. Current Status of Service System in Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway

	Hongshan Greenway	Wuchang Greenway	Qingshan Greenway
Tourist Consultation Service Center	0	0	0
Bicycle Rental Points	0	0	0
Parking Lot	4	1	7
Public Toilets	4	1	10
Sales Stations	3	3	6
Medical First Aid Points	0	0	0
Bus Stations	There are bus stations near the entrances and exits		

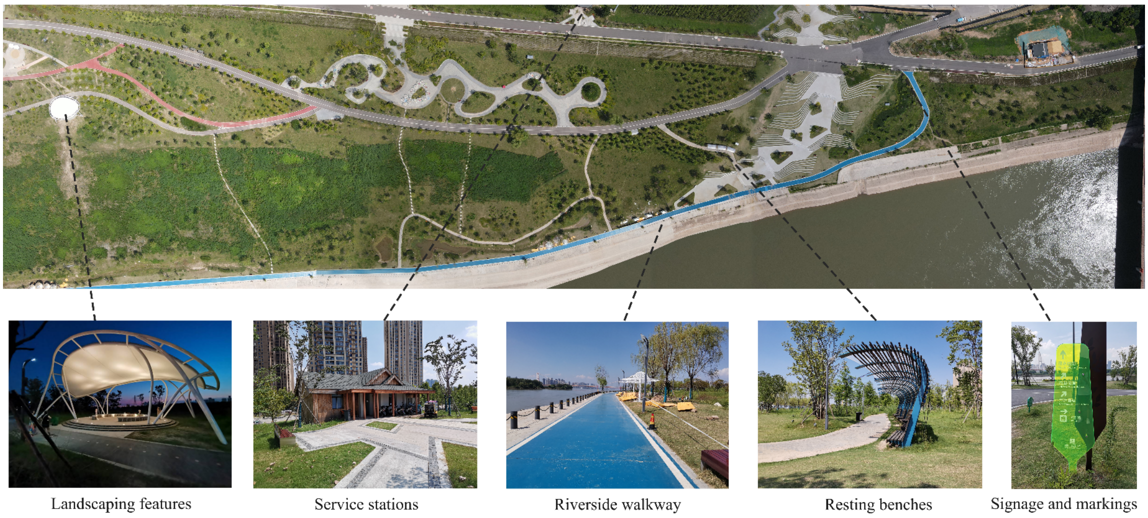

Fig. 13. Layout of Facilities in Hongshan Greenway

Fig. 14. Layout of Facilities in Wuchang Greenway

Fig. 15. Layout of Facilities in Qingshan Greenway

strips, luminous sculptures, etc., with a rich variety of lighting; Wuchang Greenway only meets the lighting of the main trails, with a single functional lighting facility and lack of attractiveness; Qingshan Greenway has complete lighting facilities, meeting the basic needs, with some changes in lighting types. In addition, all three greenways have a common shortcoming that the coverage of lighting is low. In addition to the main trails that can meet the lighting needs, the shaded paths and some landscape nodes lack lighting, and the overall feeling of the greenway at night is dim.

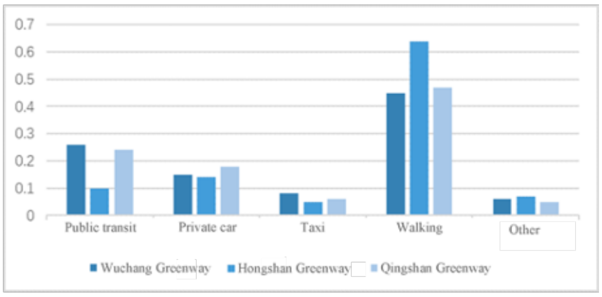

Fig. 16. Statistical Results of User Travel Methods

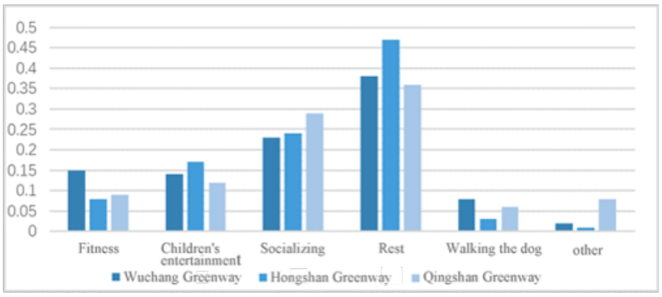

Fig. 17. Statistical Results of User Activity Preferences

5. Wuhan Riverside Greenway Use Evaluation and Analysis

5.1. Evaluation Based on User Behavior

5.1.1. Basic Information of Survey Respondents

After sorting out the questionnaires, it can be known that the gender ratio of users tends to be 1:1, most of them are local residents, and a few are tourists from other places. In terms of age composition, middle-aged and young people are also the majority, most of whom are office workers and students. In terms of travel methods, all three greenways are mainly on foot, which also indirectly reflects that the main users of the greenway are still the surrounding residents, among which the proportion of Hongshan Greenway users choosing to walk is the highest. The second is public transportation, but the proportion of public transportation travel in Hongshan Greenway is slightly lower than that of private cars, which is also related to the underdeveloped public transportation around Hongshan Greenway and the average convenience.(Fig. 16)

5.1.2. Time Rules and Activity Preferences

The research results show that the use time of users is mainly concentrated on weekends and holidays, and the morning and evening are peak periods, which just happens to be the time when students are dismissed from school and office workers get off work. For surrounding residents, it is a good time for leisure or exercise. The usage frequency of users is mostly once or twice a week or three to four times a week. Among the survey respondents of the three greenways, leisure, children's entertainment, and social interaction are the top three needs, which is related to the functional positioning of the riverside greenway and people's daily needs. (Fig. 17)

5.1.3. Analysis of Greenway Space Usage Characteristics Based on Behavior Maps

Behavior maps use different behavioral graphic symbols to record various types of behaviors in a place, which can be used to study the behavioral patterns of users and compare the actual usage with the intended situation. The record of the behavior maps this time were taken at dawn (6:30-7:30) and evening (18:30-19:30) on three weekends, which are also the peak flow times. The author has comprehensively organized the number of people using each functional area during the two time periods to finally obtain the behavior maps of the three riverside greenways.

Through Figures 18 to 20, among them, the greenway with the largest flow of people is Wuchang Greenway, followed by Qingshan, and finally Hongshan. The types of activities of the user groups include walking, running, fitness, leisure, children's entertainment, and stopping to enjoy the view. Walking and running as the main activities are widely distributed and relatively concentrated in some areas, such as the riverside walkways; leisure groups mainly stay on the rest seats next to the slow-moving paths; fitness groups are relatively few and mainly distributed in scattered fitness areas; children's entertainment activities are gathered in designated children's activity areas; people who stop and stay are distributed at nodes, mostly taking photos and viewing the river.

Overall, the three greenways have a high usage frequency and are in good condition, but there are also some problems. First, the utilization rate of some spaces is low. For example, fitness, as a main function attached to the greenway, is not frequently used in the fitness area of Wuchang Greenway. The main reasons are outdated facilities, average environmental hygiene, and poor visibility. Hongshan Greenway, due to its ongoing construction, has not yet formed a systematic fitness area and needs to be strengthened. The second issue is about the placement of rest seats. At present, the rest seats of Wuchang Greenway and Qingshan Greenway are

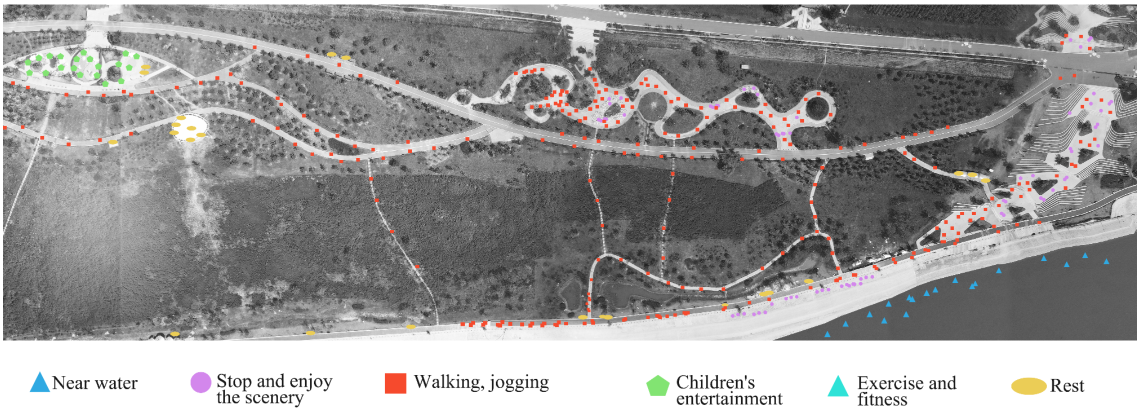

Fig. 18. Behavior Map of Hongshan Greenway

Fig. 19. Behavior Map of Wuchang Greenway

Fig. 20. Behavior Map of Qingshan Greenway

basically arranged along the edge of the path. However, for large areas of green space, these seats cannot provide shade and shelter from rain for users and may also shorten their service life. In contrast, the rest seats of Hongshan Greenway are arranged according to the surrounding environment with different rest seats, which are both aesthetically pleasing and practical.

5.1.4. Summary of User Behavior Characteristics

From the basic information and travel methods of the users of the three greenways, the main user groups of the three greenways differ in age structure, occupational characteristics, and place of belonging. Different types of user entities will also affect the functional positioning of the greenways, and corresponding configurations should be made in the service facilities and functional facilities of the greenways; from the user's activity preferences,

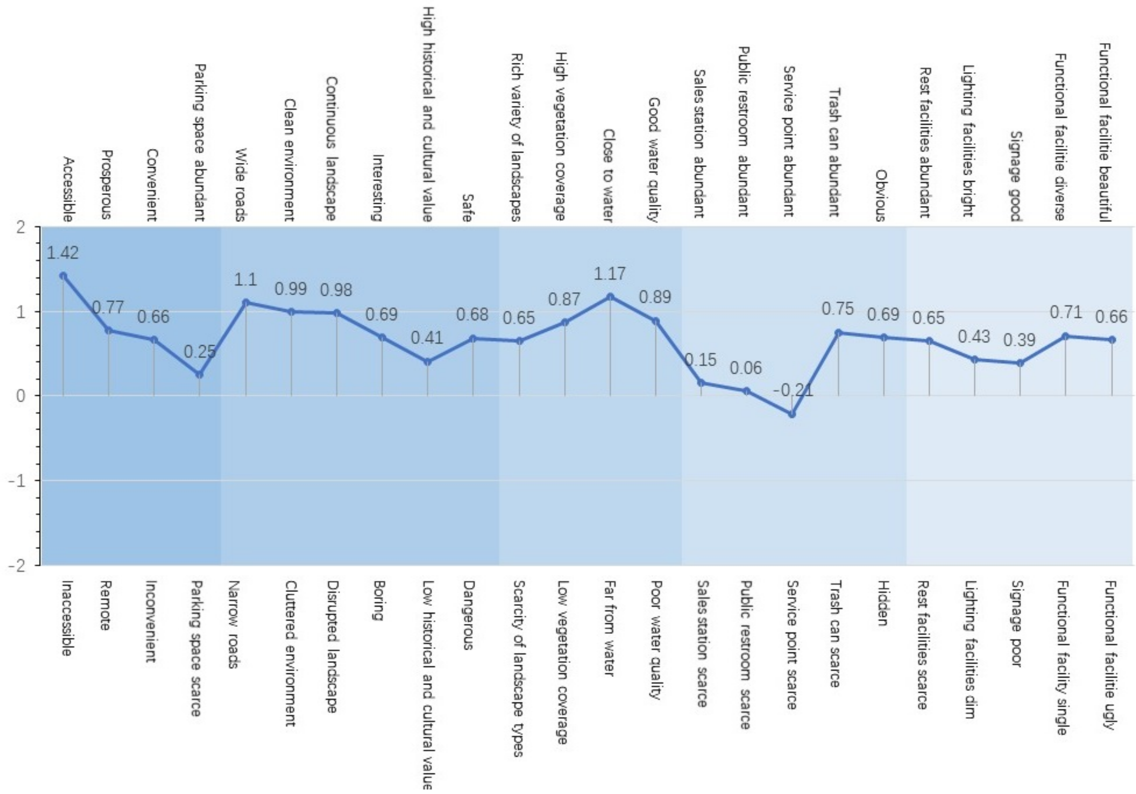

Fig. 21. SD Curve Chart of Hongshan Greenway

people tend to engage in activities such as walking, resting, socializing, and children's entertainment. Therefore, places such as riverside walkways, children's entertainment areas, and rest seats have a larger number of users and obvious signs of use. The daily maintenance and management of these areas need to pay more attention to ensure the safety and aesthetics of the greenway interior.

5.2. Satisfaction Evaluation

During the survey, questionnaires were distributed to users of the three greenways on-site and online, and interviews were conducted to statistically evaluate the satisfaction of user groups with various aspects of these three greenways. A total of 100 questionnaires were distributed for each river beach greenway, with 93, 89, and 87 valid questionnaires collected for Wuchang, Qingshan, and Hongshan Greenways, respectively, totaling 269 valid questionnaires. Then, the final scores were obtained based on the weight of each evaluation index and the questionnaire scores.

5.2.1. SD Analysis

5.2.1.1. Hongshan Greenway

From Figure 21, there is 1 negative factor in the entire curve. In the service system, "Few Service Points - Many" scored the lowest with a factor value of -0.21. In location conditions, "Inaccessible - Accessible" scored the highest with a factor value of 1.42. Looking at the entire SD curve, users generally rate Hongshan Greenway as average.

5.2.1.2. Wuchang Greenway

As shown in Figure 22, there are 5 negative factors in the entire curve. In location conditions, "Scarce Parking Lots - Abundant" has a factor value of -0.32. In the functional facility system, "Dim Lighting Facilities - Bright" is a negative value with a factor value of -0.15. The service system has 3 negative values, indicating issues such as insufficient number of sales stations, inadequate public toilet facilities, and lack of service points. Overall, the slow traffic system and landscape system are highly rated, while the service system is rated the lowest, with users generally rating Wuchang Greenway as average in overall satisfaction.

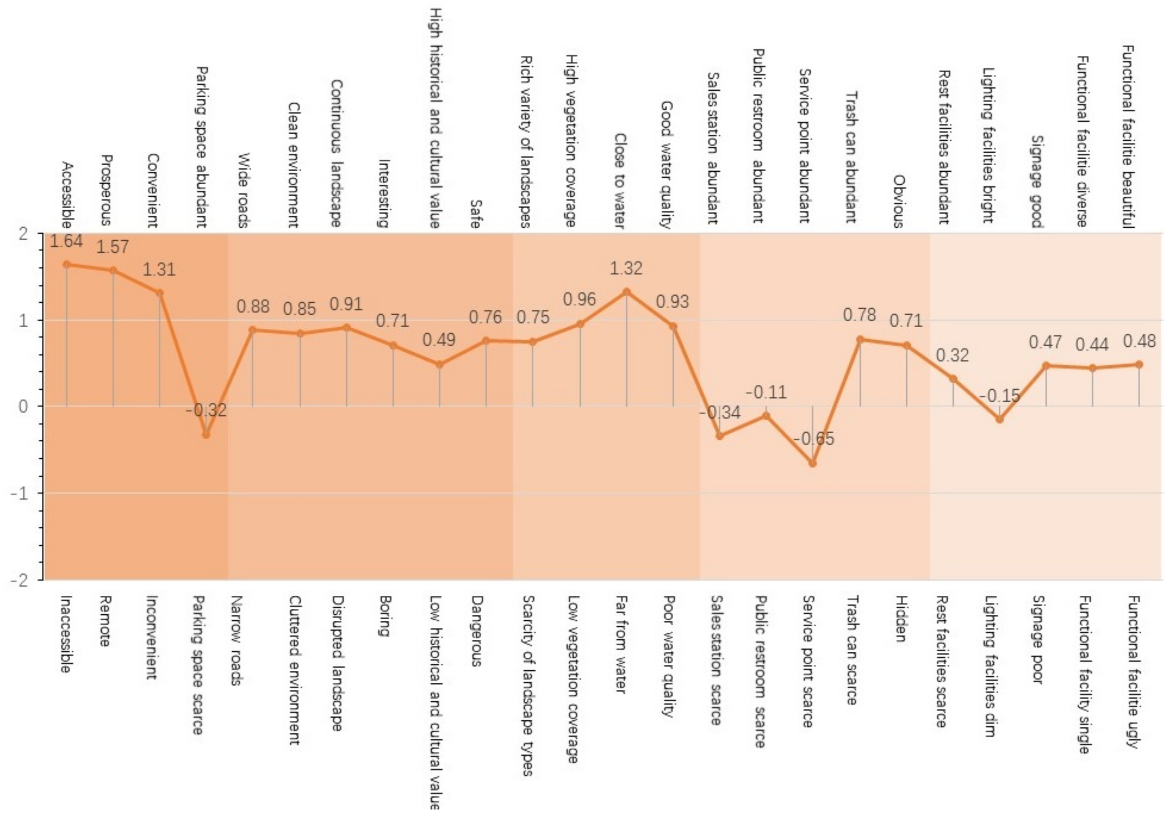

Fig. 22. SD Curve Chart of Wuchang Greenway

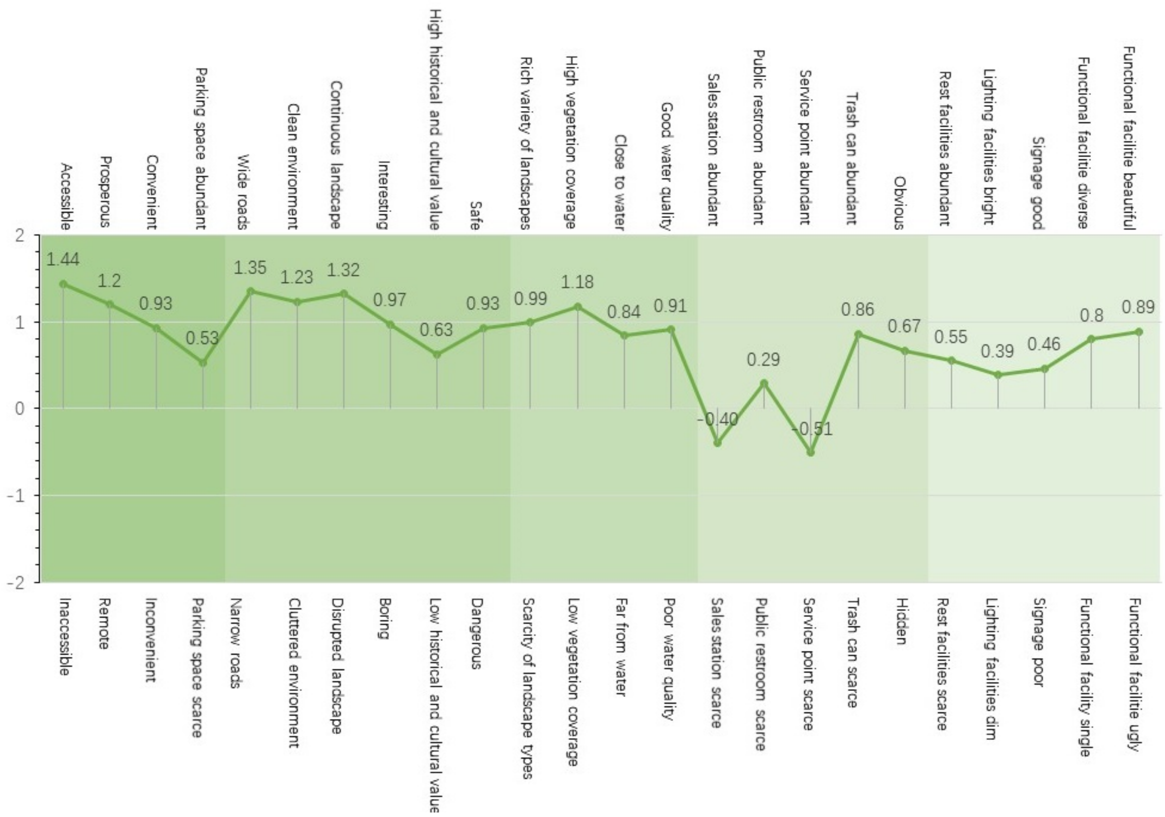

Fig. 23. SD Curve Chart of Qingshan Greenway

5.2.1.3. Qingshan Greenway

From Figure 23, there are 2 negative factors in the entire curve. The service system has 2 negative values, indicating issues such as insufficient number of sales stations and lack of service points. Overall, the location conditions, slow traffic system, and landscape system are highly rated in satisfaction, while the service system is rated the lowest. Users generally rate Qingshan Greenway as having good overall satisfaction.

5.2.2. Fuzzy Comprehensive Evaluation

Based on the SD factor values obtained from the research of the three greenways, weighted calculations were performed using the weight values obtained from the aforementioned AHP, and to more intuitively display the evaluation results, the results were converted to a percentage system. The calculation formulas are as follows:

Among them, Formula (5) converts the SD factor values into a percentage system, where SDi represents the original score of the secondary evaluation factor, and Ti represents the converted score of the SD factor. Formula (6) uses the weight to calculate the comprehensive score of the criterion layer based on the converted SD scores, where Ki is the weight value of the factor. Formula (7) serves to evaluate the final score of the greenway satisfaction, which

$$T_i = 20(SDi + 3) \tag{5}$$

$$F_i = \sum_{i=1}^{n} T_i K_i \tag{6}$$

$$D = \sum_{i=1}^{n} F_i K_i \tag{7}$$

is calculated in a similar way to Formula (2). The final results are shown in Table 7.

According to the SD factor scoring standard corresponding to the percentage system, satisfaction can be divided into 5 levels, with specific evaluation criteria as shown in Table 8.

Combining Table 7. and Table 8., the following conclusions can be drawn for the three greenways:

Wuchang Greenway has good satisfaction in location conditions and landscape system, attracting more residents and tourists with its good accessibility and environmental landscape conditions. However, the overall satisfaction is pulled down by issues such as lack of service points and dim lighting facilities. In comparison, Wuchang Greenway has the lowest satisfaction among the three greenways.

Qingshan Greenway has well integrated with the local historical and regional characteristics and has made significant improvements in environmental landscape. The shortcomings lie in the insufficient

Table 7. Satisfaction Evaluation Scores of Riverside Greenways

	Wuchang Greenway	**Qingshan Greenway**	**Hongshan Greenway**
Location Conditions	85.2	83.3	79.2
Slow Traffic System	75.6	81.6	76.4
Landscape System	79.8	79.6	78.1
Service System	63.5	65.9	66.7
Functional Facilities System	65.3	71.7	71.4
Overall Score	70.2	73.5	71.5

Table 8. Satisfaction Evaluation Grade Division Standard for Riverside Greenways

Score Range	**Satisfaction Level**	**Grade**
90-100	Very Satisfied	Excellent
80-90	Comparatively Satisfied	Good
70-80	General Satisfaction	Average
60-70	Comparatively Dissatisfied	Poor
＜60	Very Dissatisfied	Very Poor

Table 9. Summary of POE Evaluation for Riverside Greenways

Research Object	Features	Advantages	Disadvantages
Wuchang Greenway	Located in the city's core area with high foot traffic and a narrow, elongated space.	Convenient transportation, high space utilization rate, strong water affinity.	Aging service facilities, lack of configuration.
Qingshan Greenway	Located in a general city area with high accessibility and larger space.	Rich in historical and cultural characteristics, diverse functional facilities, rich landscape levels.	Large spatial scale, insufficient water affinity; slightly lacking service facilities.
Hongshan Greenway	Located in a general city area with a larger space.	Exquisite public service facility design, good spatial experience.	Inconvenient transportation, incomplete functional facilities, greening environment to be improved.

internal functional service facilities. In comparison, Qingshan Greenway has the highest satisfaction.

Hongshan Greenway is still under construction, with insufficient transportation convenience and public service facility completeness. However, with the completeness of existing facility planning and the detail of design, people have good expectations for the future construction of Hongshan Greenway, thus it still has a certain level of satisfaction.

5.2.3. Summary of Satisfaction Evaluation

Summarizing the POE evaluation results, it can be known that the three greenways each have their strengths and weaknesses (Table 9.). Qingshan Greenway has gained the highest user satisfaction with its distinctive historical and cultural characteristics and well-equipped public service facilities, but there are still deficiencies in water design and service facility configuration; Wuchang Greenway has the highest flow of people due to its good location conditions, but due to the early construction time, the existing public service facility configuration cannot meet the current needs of people, and more consideration is needed in environmental design details; Hongshan Greenway currently cannot fully meet people's needs due to imperfect public transportation system, insufficient traffic convenience, and poor completeness of public service facilities and environmental landscape.

6. Optimization Suggestions for Wuhan Riverside Greenway

6.1. Strengthen the Design of Characteristic Water-Affinity Spaces

With the unique water resource conditions of the riverside greenway, people have a strong affinity for water. In the design of waterside spaces, the main aspects are visibility, approachability, and touchability. Through research, it has been found that the three greenways have achieved visibility, using viewing squares, viewing platforms, viewing pavilions, and other spaces to create a distance between users and water. Compared with Wuchang Greenway, Hongshan Greenway and Qingshan Greenway need to strengthen "approachability" and "touchability", and can set up water trestles, water-affinity steps, preserve original beaches, etc.[9] (Fig. 24-25).

6.2. Improve the Functional Service System

6.2.1. Improve Site Facilities

6.2.1.1. Increase Commercial Facilities

Currently, the commercial facilities along the three greenways are insufficiently set up, with existing sales stations being too few and too far apart. Some users have also pointed out the difficulty of purchasing water and food within the greenways, and many sales stations are set up but not in operation, sometimes necessitating the purchase of items outside the greenway, which brings great inconvenience to the journey. To meet user needs, sales stations can be set up in large squares, fitness squares, or children's playgrounds where there is a large flow of people, and other important nodes can be replaced with vending machines (Fig. 26).

6.2.1.2. Add Public Toilets

According to field research, the number of public toilets along the three greenways is insufficient and does not meet the demand. Wuchang Greenway

Fig. 24. Current Status Map of Water-Affinity Spaces for Hongshan Greenway, Wuchang Greenway, and Qingshan Greenway

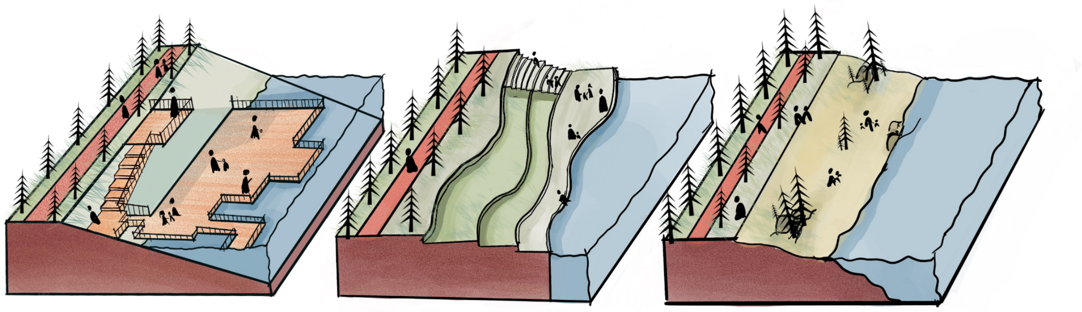

Fig. 25. Analysis of Water-Affinity Space Design Techniques

only has one public toilet set up. The following optimization strategies are proposed:

Set up regular toilets in places with dense pedestrian traffic, and set up mobile toilets in other areas to ensure that toilets can be found within a 10-minute walk; the setting of toilet squat positions should be designed according to the characteristics of the number of people in the area, at a ratio of 50 people per toilet, while also considering the addition of women's toilets, mother and baby dedicated toilets, and accessible toilets (Fig. 26).

6.2.1.3. Set Up Service Points and First Aid Medical Points

Currently, the number of service points and first aid medical points along the three greenways does not meet user needs. There are few service points, and some areas are not within the service radius. It is necessary to add service points in conspicuous locations and provide clear signs for users. In addition, all three greenways lack first aid medical points. It is recommended to set up first aid medical points in sections with moderate foot traffic and good accessibility to handle emergencies within the greenway and ensure the safety of users[9]. (Fig. 26).

6.2.1.4. Increase the Number of Rest Facilities

In the long linear space, rest benches should be set up along the way, and a large rest pavilion should be set up at regular intervals, combined with the landscape. This can serve as a place for daily rest and communication, and can also become a secondary node of the greenway, increasing the continuity of the spatial sequence (Fig. 26).

6.2.1.5. Improve Lighting Facilities

In the three greenways, some areas have single lighting facilities with poor lighting effects. It is advisable to use ground lights, luminous sculpture pieces, and characteristic streetlights to increase the types of lighting and enhance the richness of the landscape. At the same time, solar-powered streetlights using photovoltaic power generation can be arranged along the walkways to save resources and implement sustainable development (Fig. 26).

6.2.2. Improve Parking Spaces

During the research process, it was found that the parking spaces of Wuchang Greenway do not meet the usage requirements at all. Wuchang Greenway is accessible, convenient for transportation, and well-known, attracting many people to visit every

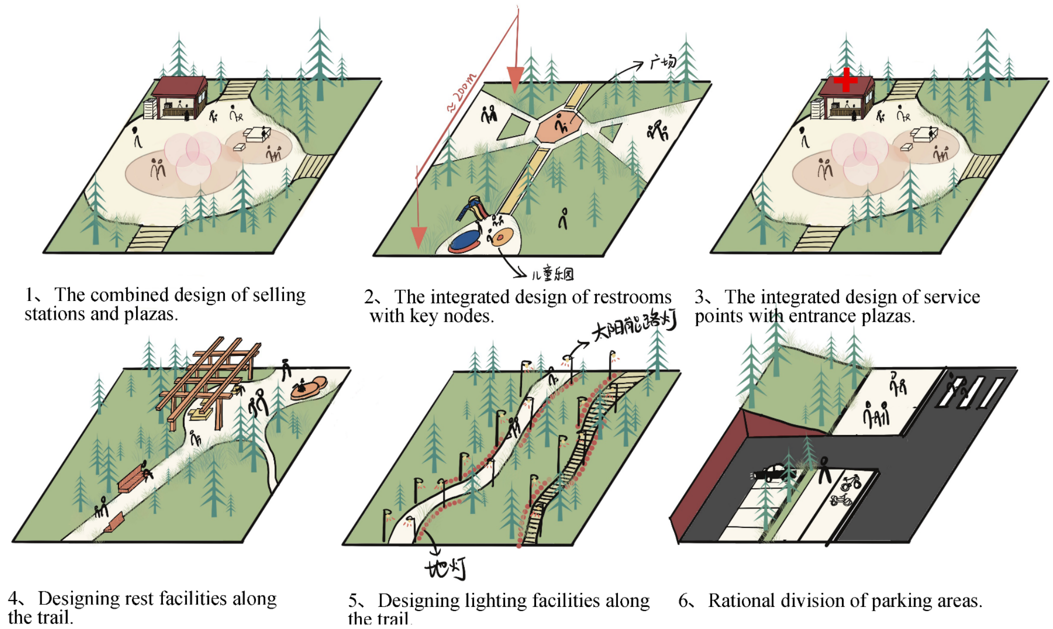

Fig. 26. Site Facilities Design Analysis Diagram

day. The available parking spaces are insufficient, leading to random parking on the street sidewalks, traffic congestion, and overcrowded roads. To solve these problems, the situation can be improved by building underground parking lots around, reasonably dividing parking areas, and increasing ground non-motor vehicle parking spaces (Fig.26).

6.2.3. Enrich the Types of Slow Traffic Systems

At present, the main slow traffic systems of the three greenways include pedestrian systems and sightseeing tour car systems, lacking a bicycle tour system. In the future, the types of slow traffic systems should be improved, and a dedicated bicycle riding greenway should be set up to enrich the types of visitors' tours. At the same time, pay attention to improving the barrier-free transportation system. Cycling activities are closely related to the barrier-free transportation system. The lack of a barrier-free transportation system may make it difficult or impossible for cycling vehicles to enter the cycling path[15].

7. Conclusion

Urban waterfront greenways, against the backdrop of transitioning from an era of growth to an era of stock, are constantly progressing and developing as one of the important strategies for low-carbon city construction, with their multifunctional characteristics of connecting public spaces, activating urban vitality, driving regional development, and restoring aquatic ecological environments. However, at the same time, it is still necessary to examine the current built environment of urban waterfront greenways from different perspectives and to think about the future development and construction of waterfront greenways, in order to build a waterfront greenway that prioritizes ecology and people.

References

1. Liu Guili, Jianghe, Zhou Aihua, Niu Haipeng, Constructing a Theoretical Framework for Ecological Environment Zone-based Governance under the Dual Carbon Target, Environmental Protection 50 (n.d.) 39–43. https://doi.org/10.14026/j.cnki.0253-9705.2022.09.016.
2. Huang Runqiu, Building a Beautiful China Where Humans and Nature Coexist Harmoniously, China Ecological Civilization (n.d.) 13–16.
3. Liu Yueqin, Lin Xuanquan, Urban Waterfront Recreation Planning and Design: A Case Study of Zhangjia Bang in Pudong, Shanghai, Chinese Landscape Architecture (n.d.) 25–30.
4. Zhang Dou, The Reunion of the City and the River, Architectural Journal (n.d.) 6–10.
5. Liu Shengwei, Ding Rong, Bai Yang, Practice and Reflection on Greenway Construction in Urban Renewal, Chinese Landscape Architecture 37 (n.d.) 40–43. https://doi.org/10.19775/j.cla.2021.S1.0040.
6. Liang Chen, Zeng Jian, Post-Occupancy Evaluation (POE) Research on Urban Waterfront Walking Environment, Building Energy Efficiency 46 (n.d.) 72–78.
7. Dong Baoying, Cao Xu, Ma Shumin, Fan Xinyu, Chen Yu, Optimization Strategy for Urban Park Water Space Based on Post-Occupancy Evaluation: A Case Study of Xuanwu Lake Park, Jiangsu Agricultural

Sciences 50 (n.d.) 153–158. https://doi.org/10.15889/j.issn.1002-1302.2022.22.022.

8. Li Haisheng, Yang Queping, Zhao Yanming, Constructing a Theoretical Framework for Ecological Environment Zone-based Governance under the Dual Carbon Target, Journal of Environmental Engineering Technology 12 (n.d.) 336–347.
9. Wang Yuhang, Urban Riverside Greenway Usage Evaluation Study: A Case Study of the Riverside Greenway in Qingshan District, Wuhan City, [Master's Thesis], Wuhan University, 2020.
10. Yuan Xihang, Post-Occupancy Evaluation of Changsha Yanghu Waterfront Greenway Based on the SD Method, [Master's Thesis], Hunan University, 2019.
11. Meng Ge, Post-Occupancy Evaluation Research on Waterfront Space of Weihe Qinhan New City Section, [Master's Thesis], Xi'an University of Architecture and Technology, 2022.
12. Ding Chunlu, Ma Jianxiao, Zhu Ning, Comprehensive Evaluation Research on Urban Greenways Based on the AHP, Forest Engineering 36 (n.d.) 81–90. https://doi.org/10.16270/j.cnki.slgc.2020.02.013.
13. Han Lei, Xie Shuangyu, The Process and Mechanism of Urban Waterfront Public Recreation Space Production in Wuhan, Human Geography 37 (n.d.) 183–192. https://doi.org/10.13959/j.issn.1003-2398.2022.06.020.
14. Wang Jing, Xu Feng, Urban Ribbon Park Design Led by Landscape Nodes, Chinese Landscape Architecture 26 (n.d.) 77–80.
15. Xu Minghui, Wang Hao, Chen Zhanchuan, Post-Occupancy Evaluation and Improvement Strategy Research on Slow Greenway of Haikou Bay Waterfront Park from a Green and Healthy Perspective, Landscape Architecture 39 (n.d.) 123–129.

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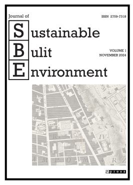

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Short-term Traffic Flow Prediction: A Method of MEA-LSTM Model Based on Chaotic Characteristics Analysis

Zixuan Zhang [a], Dongliang Zhao [b], Yan Li [c], Zhe Huang [d,*]

[a] *School of Transportation Engineering, Chang'an University, Xi'an 710064, China*
[b] *Shandong Provincial Communications Planning and Design Institute Group Co., LTD, Jinan 250002, China*
[c] *School of Civil Aviation, Northwestern Polytechnical University, Xi'an 710072, China*
[d] *Hebei Xiong'an New Area Management Committee Construction and Transportation Management Bureau, Xiong'an 070001, China*

KEYWORDS

short-term traffic flow prediction,
intelligent transportation,
chaotic characteristics,
machine learning

ABSTRACT

To effectively improve the accuracy of short-term traffic flow prediction, an improved Long Short-Term Memory (LSTM) method is proposed using the Mind Evolution Algorithm (MEA). Firstly, to address the issues of abnormal and missing traffic flow data, a Neighborhood Stacked Denoising AutoEncoder (NSDAE) is used for data repair. Then, the maximum Lyapunov exponent is used to determine the chaotic characteristics. Meanwhile, based on Bayesian estimation theory, the features of three-parameter sequences are fused in high-dimensional space using phase space reconstruction technique to obtain reconstructed multi-parameter fused traffic flow data. Finally, by taking advantage of the fact that MEA can divide the data into several subpopulations for optimal search separately, a prediction model based on MEA to improve LSTM is proposed. The results show that compared to the other two traditional data restoration methods, the NSDAE has higher accuracy, with the lowest average values of RMSE, MAE, and MAPE. Through the phase space reconstruction technique, the feature fusion of three parameters of traffic flow is realized in high-dimensional space, which makes up for the insufficiency of a single time-series data that cannot comprehensively levy the characteristics of traffic flow. The MEA-LSTM model outperforms the LSTM model in terms of prediction accuracy, computational efficiency, and generalization ability, and its RMSE, MEA, and MAPE are reduced by 24.3%, 28.9%, and 30.1%, respectively.

1. Introduction

Under the background of intelligent transportation, the use of traffic big data to predict future traffic conditions and reasonably guide residents to travel according to the prediction results is an effective way to alleviate traffic congestion [1]. In traffic state prediction, short-time traffic flow prediction (less than 15 min) is a very important branch, which has high practical application value in travel path optimization, traffic diversion, dynamic signal control, and other aspects [2]. At present, due to the sufficient access to traffic big data and the relative maturity of deep learning theory, the adoption of deep neural networks as the core methodology of short-term traffic flow prediction has become a hot-

* Corresponding author at: Hebei Xiong'an New Area Management Committee Construction and Transportation Management Bureau, Xiong'an 070001, China.
E-mail address: huangzhe@xiongan.cn (Zhe Huang)

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spot and mainstream of research [3]. AutoEncoders (AE), Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Gated Recurrent Unit (GRU), Graph Neural Networks (GNN), and various composite deep neural network models have been used in the field of short-term traffic flow prediction [4-8].

As a kind of RNN, the Long Short-Term Memory (LSTM) shows its powerful time series processing ability in short-term traffic flow prediction, which is especially suitable for dealing with such complex and time-series data as traffic flow. LSTM is designed to combine the short-term and long-term temporal information and exhibits superior time-series prediction performance [9]. Yang et al. proposed a short-term traffic flow prediction method, LSTM+, that can sense both long short-term memory and remarkably long distances. This method can effectively improve the problem of the LSTM extremely long-term memory shortage [10]. Wei et al. constructed an AE-LSTM prediction method. AE obtained the internal relationship of traffic flow by extracting the features of upstream and downstream traffic flow data, and the LSTM network utilized the obtained feature data and historical data to predict complex linear traffic flow data [11]. To promote the forecast accuracy, Zhao et al. proposed a novel traffic forecast model based on LSTM network that considered temporal–spatial correlation in traffic system via a two-dimensional network which was composed of many memory units [12].

However, data completeness and validity are the basis for traffic flow prediction. Traffic flow data comes from multiple sources and the patterns in the data are multimodal, which results in less accurate predictions if only a single variable is considered [13]. Although LSTM networks have achieved good results in traffic flow prediction, insufficient data continuity, lack of integrity, and incomplete inclusion of information will greatly reduce the prediction performance of LSTM [14]. For this reason, many scholars based on the chaotic characteristics of traffic flow parameters, traffic flow phase space reconstruction in order to obtain complete information, comprehensive content of high-quality traffic flow data [15-17]. In addition, the prediction performance of LSTM networks is affected by the hyperparameters (number of nodes in the hidden layer, number of iterative cycles, initial learning rate) [18]. Optimizing the hyperparameters can make the model fit the training data better, improve the prediction accuracy and enhance the generalization ability [19].

Given the above research deficiencies, this paper firstly proposes a Neighborhood Stacked Denoising AutoEncoder (NSDAE) method used for traffic data repair, and highlights its effect by comparing with many other data repair methods. Then, the repaired data is subjected to chaotic system determination, while phase space reconstruction is carried out, and the chaotic characteristics of the three parameters of traffic flow are analyzed. Aiming at the problem that a single traffic flow parameter cannot characterize all the features of the traffic system, the Bayesian estimation theory is introduced to fuse multiple traffic flow parameters in the phase space, and the phase space reconstruction sequence containing multiple traffic flow feature information is obtained, which provides an effective data basis for traffic flow prediction. Finally, by combining the respective advantages of the Mind Evolution Algorithm (MEA) and LSTM model, an improved LSTM prediction method based on the MEA is proposed, and a comparative analysis of the prediction accuracy of the MEA-LSTM model is carried out in terms of prediction accuracy, prediction efficiency, and generalization ability to validate the accuracy of the model.

2. Dataset description

2.1. Data source

This paper used traffic volumes, average location speeds, and lane occupancy rate to characterize traffic flows. The data were obtained from the Performance Measurement System (PeMS), a freeway performance evaluation system developed by the California Department of Transportation in conjunction with the University of California, Berke-

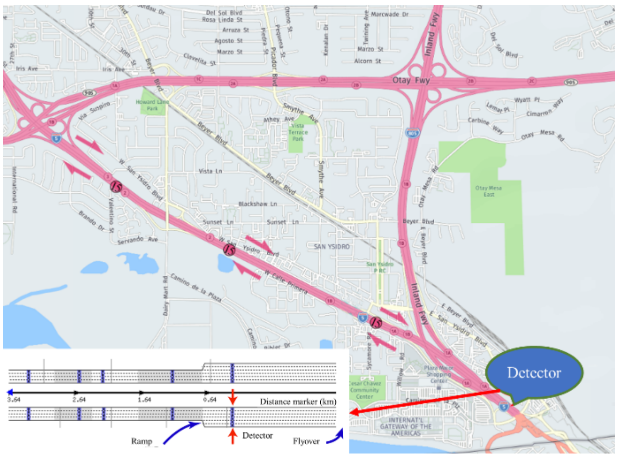


Fig. 1. Target detector location

Table 1. The examples of the raw data

5 Minutes	Flow (Veh/5 Minutes)	Occupancy (%)	# Lane Points	% Observed	Speed (mph)
5/4/2023 0:00	6	0.20	4	75.00	67.10
5/4/2023 0:05	7	0.20	4	75.00	67.00
5/4/2023 0:10	6	0.20	4	75.00	69.60
5/4/2023 0:15	9	0.20	4	75.00	67.80
5/4/2023 0:20	10	0.30	4	75.00	64.50
5/4/2023 0:25	7	0.20	4	75.00	69.10
5/4/2023 0:30	9	0.20	4	75.00	68.80
5/4/2023 0:35	4	0.10	4	75.00	69.00
5/4/2023 0:40	4	0.10	4	75.00	70.10
…	…	…	…	…	…

ley. As shown in Fig. 1, the data detected by detector number 1118326 in the I5-S freeway was selected as the base dataset. Further, the traffic data collected by this detector from May 4, 2023, to May 30, 2023, a total of 27 days of actual roadway measurements, with a data recording interval of 5 min, which meets the requirement of short-term traffic flow prediction duration. The data recording interval of the detector shows that 288 groups of data can be obtained in a single day and a total of 7775 groups of traffic data in the selected period. The examples of the raw data are shown in Table 1.

2.2. Data patching

Due to the internal failure of the detector, external changes, and other reasons, the detector data acquisition process results in erroneous data and missing data. Therefore, before the establishment of the traffic flow prediction model, it is necessary to deal with data redundancy, temporal drift, error, loss, and other phenomena occurring in the process of data acquisition [20].

This paper proposed the Neighborhood Stacked Denoising AutoEncoder (NSDAE) model to fill the traffic flow data. Neighborhood is a commonly used method in deep learning, the core of which is to fill in the missing data using the data within the neighborhood of the missing data [21]. Due to the spatio-temporal similarity characteristics of traffic flow data, its missing data are more appropriately handled by the neighborhood correlation filling method. At the same time, combined with Stacked Denoising AutoEncoder (SDAE), different neighborhoods are selected in different times, and the features of the neighborhoods at the missing moments are fully extracted, and then the data are filled in, so as to increase the robustness of the filler

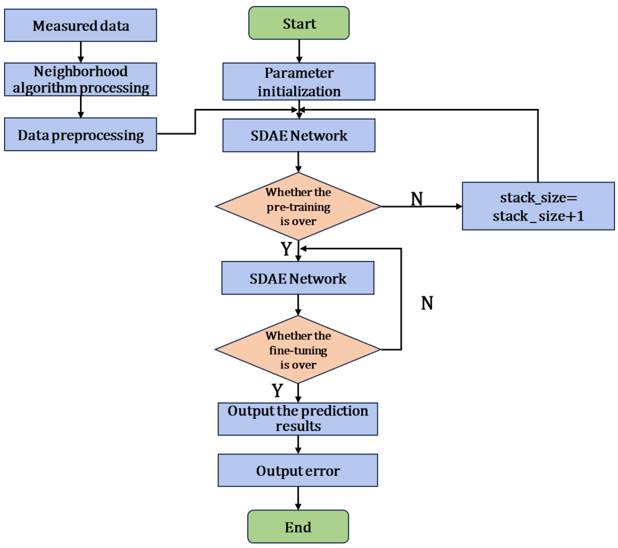


Fig. 2. NSDAE model structure diagram

model, and the data can be obtained closer to the real data [22, 23]. The data patching process for NSDAE is shown in Fig. 2.

NSDAE model is written in Python, where the neighborhood part is written using the NumPy scientific database and the AE part is built with the deep learning framework Keras. The parameter combinations for the NSDAE model are: the missing rate is 10%, the number of SDAEs is 2, each SDAE has three hidden layers, the number of nodes in each SDAE hidden layer is {128, 64, 128}, *window_n=10*, *batch_size=288*, and the number of iterations is 200.

3. Methodology

3.1. Theory of chaotic properties of traffic flow

3.1.1. Lyapunov exponent

Lyaponuv exponent represents a numerical characteristic of the average exponential divergence of neighboring trajectories in phase space and is often used to determine the chaotic nature of a system [24]. When the dynamical system becomes an n-dimensional discrete system xn+1=F(xn), there exists n Lyapunov exponents $\gamma_1, \gamma_2, ... \gamma_n$, Each of γ_i exhibits the motion characteristics of the corresponding orbit. In determining the trajectory of an n-dimensional discrete system, n Lyapunov exponents are generated. The largest of these is called the maximal Lyapunov exponent. If the maximum Lyapunov exponent is positive in a high-dimensional dynamical system, it indicates that the system exhibits chaotic characteristics [25].

3.1.2. Correlation dimension

Correlation dimension D(m) is a measure of the amount of characteristic information contained in chaotic attractors [26]. In chaotic systems, D(m) tends to saturate as the embedding dimension m of the time series increases, so the correlation dimension can also be used as a metric for the determination of chaotic properties. Genetic programming (G-P) algorithm can obtain the time series m by solving the association function [27]. When m increases, if D(m) gradually tends to saturation, then the system satisfies the chaotic property, and D(m) corresponding to the saturation state is the correlation dimension of the attractor of the time series. If the system does not have chaotic properties, D(m) will not tend to saturation, but will grow to positive infinity as m grows [28].

3.1.3. Phase space reconstruction of multiparameter time series

Since the traffic flow data is a one-dimensional time series, it cannot represent the existence of complex motion characteristics within the system. Therefore, the concept of phase space reconstruction needs to be introduced in order to analyze the chaotic characteristics of traffic flow data. Takens points out two parameters that need to be determined in phase space reconstruction: the embedding dimension m and the delay time τ. When selecting the values of m and τ, the connection between them usually needs to be considered [29, 30]. In addition, there is another parameter that in phase space reconstruction: the embedding window width $\tau_W=(m-1)\tau$. In this paper, the C-C algorithm is used to solve τ and τ_W.

After phase space reconstruction, it is difficult to express the complex information inside the chaotic system of traffic flow by considering only a single variable. Therefore, in order to obtain effective data with more complete representation information, this paper fused the three-parameter time series matrices reconstructed from the phase space with phase points in the high-dimensional space based on the internal connection between the three parameters of the traffic flow and based on the Bayesian estimation theory [31]. Based on the fused traffic flow data, a model is built for prediction in order to obtain higher prediction accuracy.

To determine the precise dynamical properties of a chaotic system, it is necessary to locate the strange attractor and then examine its trajectory in higher dimensional space to uncover the regularity

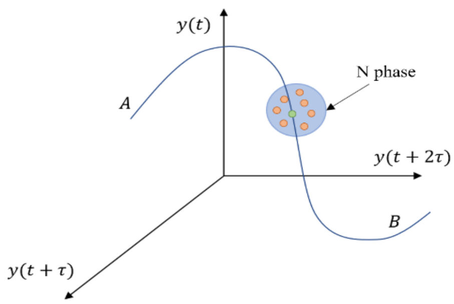


Fig. 3. Phase point distribution in phase space

of the chaotic behavior. When a chaotic system involves multiple variables, a portion of its trajectory in multi-dimensional space can be seen as illustrated in Fig. 3.

The real attractor is a phase point in its trajectory, and in principle, if we want to restore its system perfectly, the attractors of the system should all be located in a fixed orbit. However, due to the small information reserve of individual variables in phase space reconstruction, there is a partial deviation between the chaotic attractors generated after phase space reconstruction and the real attractors, which leads to the fact that the chaotic attractors generated by each variable cannot completely present the real characteristics of the original chaotic system. Therefore, these phase points need to be fused to finally obtain an optimal phase point that contains more complete information, has a higher degree of reduction, and is close to the characteristics of the real attractor. By Bayesian estimation theory, given

$$x_k^i = \left[x_{i,k}, x_{i,k+\tau}, \ldots, x_{i,k+(m-1)\tau}\right] \ \forall i = 1,2,\ldots,M;\ k = 1,2,\ldots,K \quad (1)$$

a time series of multiple variables combined, the phase space reconstruction is performed and contains K phase points, which can be expressed by Eq. (1).

$$D_k = \left[x_k^1, x_k^2, \ldots, x_k^M\right] \ \forall k = 1,2,\ldots,K \quad (2)$$

After reconstructing the phase space of the M time series, the k-th phase point of each variable is selected as the set of phase points to be fused, which can be expressed by Eq. (2).

$$P\left(Z_k \mid x_k^1, x_k^2, \ldots, x_k^M\right) = \frac{P\left(Z_k; x_k^1, x_k^2, \ldots, x_k^M\right)}{P\left(x_k^1, x_k^2, \ldots, x_k^M\right)} \quad (3)$$

If $Z_k(k = 1,2,\ldots,K)$ is a phase point after the fusion of the multi-parameter phase space, then the estimated value of $Z_k(k = 1,2,\ldots,K)$ is expressed by Eq. (3).

Assuming $Z_K \sim N(Z_0, \sigma_0^2)$, where Z_0 is the mean value of Z_k and $D_k \sim N(Z_k, \sigma_h^2)$ is the variance,

$$P\left(Z_k \mid x_k^1, x_k^2, \ldots, x_k^M\right) = \gamma \exp\left[-\frac{1}{2}\left(\left(\sum_{h=1}^{M}\frac{1}{\sigma_h^2}+\frac{1}{\sigma_0^2}\right)z_k^2 - 2\left(\sum_{h=1}^{M}\frac{x_h^k}{\sigma_h^2}+\frac{Z_0}{\sigma_0^2}\right)Z_k\right)\right] \quad (4)$$

while, $D_k \sim N(Z_k, \sigma_h^2)$ and σ_h^2 are the covariance

$$\gamma \exp[-\frac{1}{2}((\sum_{h=1}^{M}\frac{1}{\sigma_h^2}+\frac{1}{\sigma_0^2})z_k^2 - 2(\sum_{h=1}^{M}\frac{x_h^k}{\sigma_h^2}+\frac{Z_0}{\sigma_0^2})Z_k)] = \frac{1}{\sqrt{2\pi\sigma}}\exp[-\frac{1}{2}(\frac{Z_k - Z}{\sigma})^2] \quad (5)$$

matrix. Setting the parameter

$$Z = \frac{\sum_{h=1}^{M}\frac{x_h^k}{\sigma_h^2}+\frac{Z_0}{\sigma_0^2}}{\sum_{h=1}^{M}\frac{1}{\sigma_h^2}+\frac{1}{\sigma_0^2}} \quad (6)$$

$\alpha = 1/P(X_k^1, X_k^2, \ldots\ldots, X_k^M)$, the following Eq. (4) is given.

If P obeys a normal distribution, we can obtain

$$\hat{Z}_k = \int Z_k \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{1}{2}\left(\frac{Z_k - Z}{\sigma}\right)^2\right] dZ_k = z; \forall k = 1,2,\ldots,K \quad (7)$$

Eq. (5).

By solving Eq. (5), Eq. (6) can obtain:

Accordingly, the value of the estimated value $\hat{Z}_k$ of the optimal fusion phase point can be obtained by Eq. (7):

Where: K-Total number of phase points in multi-dimensional space in phase space reconstruction after multi-parameter fusion; k-th phase point in phase space reconstruction after multi-parameter fusion.

3.2. *MEA-LSTM model*

3.2.1. *MEA*

Mind Evolution Algorithm (MEA) is a machine learning algorithm that incorporates the two opposing thinking patterns of convergence and divergence found in human cognition. The core of the MEA algorithm is the continuous exploration of the data to find the optimal individual element values in many iterations. In this algorithm, convergence

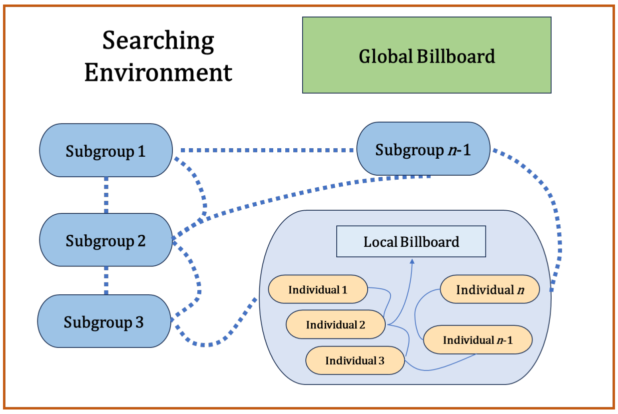


Fig. 4. The mechanism of the MEA algorithm [33]

and dissimilation operations are used to continuously generate a new and better subpopulation, and finally the optimal solution is found [32]. The specific steps of the algorithm refer to the Ref. [33]. The optimization process is shown in Fig. 4.

3.2.2. *LSTM*

LSTM is a special kind of RNN model, which has both long-time and short-time memory, and improves the gradient dispersion and gradient explosion problems of traditional RNNs. LSTM model has three threshold units, namely, forgetting gate, input gate and output gate, and transfers the information along the temporal sequence through linear operations, which has good memory because the information is re-inputted in a loop each time, and the model achieves the filtering of the input infor-

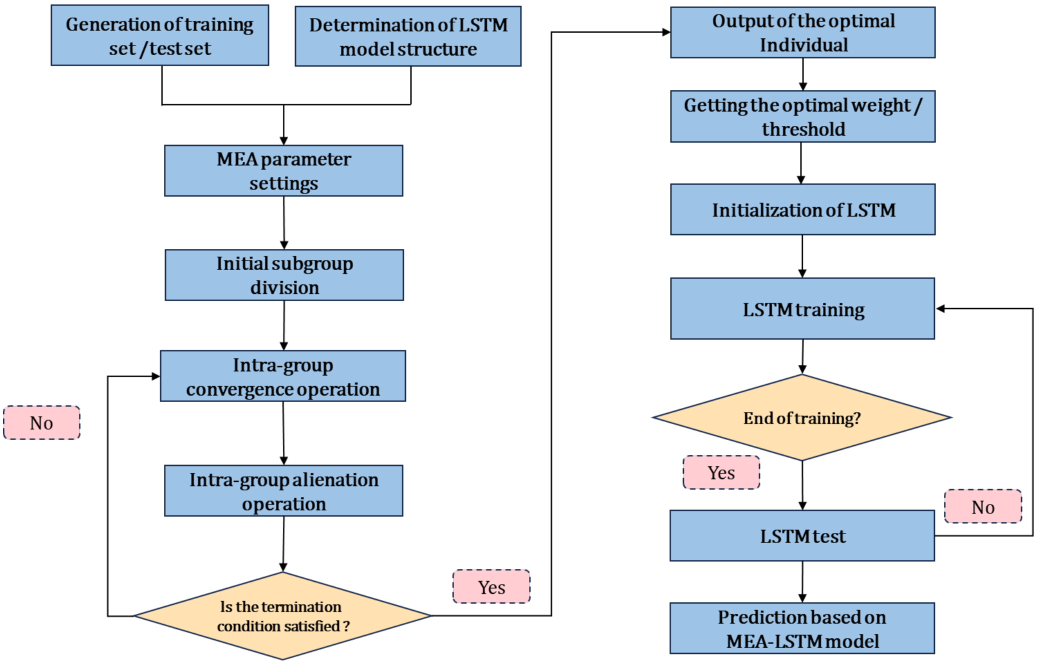


Fig. 5. MEA-LSTM model structure diagram

mation through the ' gate ' structure [34]. The model achieves the filtering of input information through the ' gate ' structure. The specific steps of the algorithm refer to the Ref. [35].

3.2.3. MEA-LSTM model

Aiming at the problems of the LSTM model, this paper improves LSTM model by introducing the MEA, which prompts the output results to reach the optimum quickly. MEA divides the data into several subpopulations for optimization search, alternates between convergence and dissimilation operations, changes the shortcomings of LSTM model parameters that can only be trained one by one, and optimizes the weights and thresholds of the LSTM model quickly. The MEA-LSTM model not only improves the convergence speed and generalization ability of the LSTM model, but also makes the initial weights and thresholds of the model more global, so that the algorithm is more accurate in predicting the traffic flow. Its modelling process is shown in Fig 5.

3.2.4. Parameterization

The traffic flow data after multi-parameter phase space reconstruction is divided into training set and test set. Valid data before 23 May is used as the training set and valid data from 23 May to 30 May is used as the test set.

After searching and trial calculation, the network structure of LSTM model is determined as a single input layer, double hidden layer and single output layer. The excitation functions are sigmoid and tanh functions, the optimization method is Adam, and the number of iterations is set to 500, and the learning rate is set to 0.03. The first 8 periods of the measured traffic flow data are selected as the input values, so the number of neurons in the input layer and the number of neurons in the hidden layer of the LSTM model are 8 and 16 respectively. The main parameters of the MEA model: the population size was set to 800, six winning subpopulations were screened during the run, and six temporary subpopulations were screened; the size of a single subpopulation was 80, and the number of iterations was 20.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \hat{x}_i - x_i^2}{n}} \tag{8}$$

$$MAE = (\frac{\sum_{i=1}^{n} |\hat{x}_i - x_i|}{n}) \tag{9}$$

$$MAPE = (\frac{\sum_{i=1}^{n} |\hat{x}_i - x_i|}{n}) \tag{10}$$

3.2.5. Evaluation indicators

Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and Root Mean Square Error (RMSE) were used to assess the accuracy of the model's prediction results, as shown in Eqs. (8)-(10):

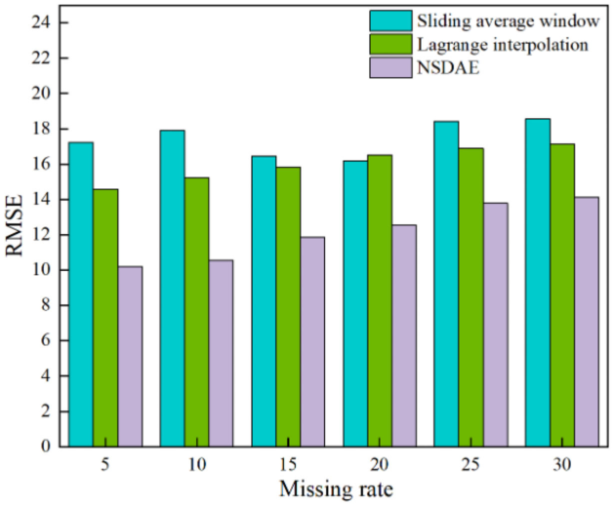
Where: $\hat{x}_i$ - predicted value; x_i - observed value; n - Length of time series data.

4. Results and discussions

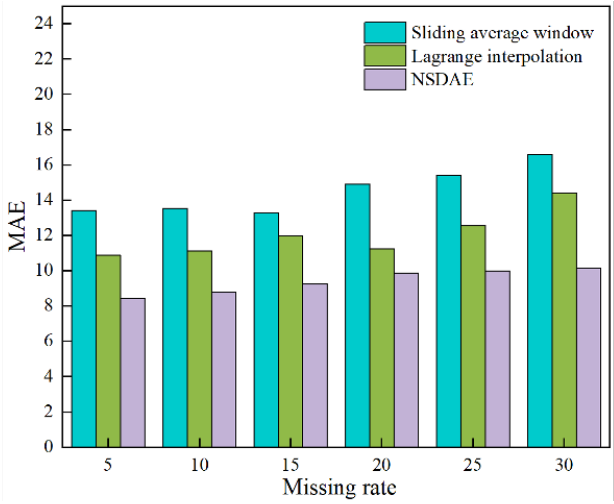
4.1. Evaluation of the results of data patching

In order to show the performance of NSDAE method, this paper selects two commonly used data patching methods: the sliding average window method [36] and the Lagrange interpolation method [37] for comparative analysis, and evaluates them in combination with the error metrics. Under the setting of different data missing rate, NSDAE, sliding average window method and Lagrange interpolation method are used for data restoration, respectively. The error results of the three methods were obtained when the value interval of the missing data rate was set to [5,30] and the value interval was 5%, as shown in Fig. 6.

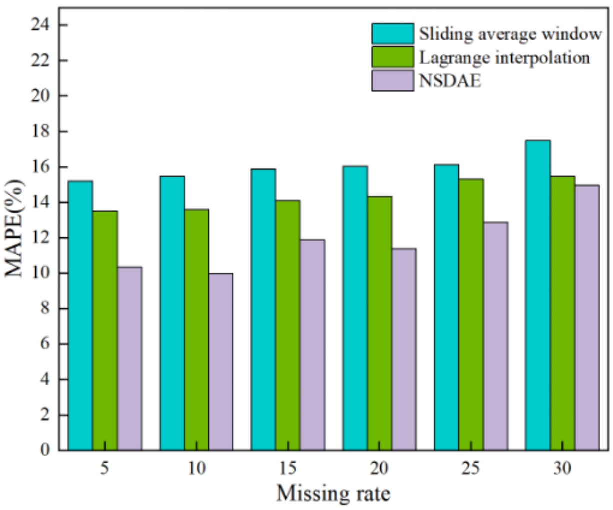
As can be seen from Fig. 6, the errors of all three models show an upward trend with the increase of the missing data rate, with the Lagrange interpolation and NSDAE floating more stably, while sliding average window method fluctuates more. As a whole, when the value interval of the missing data rate is [5,30] and the value interval is 5%, the average value of RMSE of NSDAE is 12.174, the average value of MAE is 9.416, and the average value of MAPE is 11.908%, which is the lowest value in all three models. It can be concluded that the error data repair results of NSDAE are significantly better than the other two methods.



(a) RMSE



(b) MAE



(c) MAPE

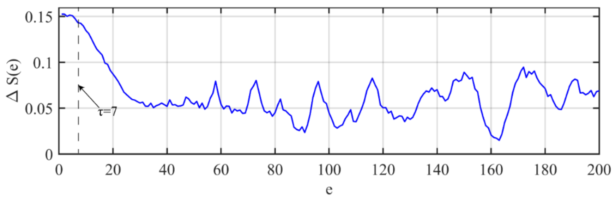
Fig. 6. Comparison of the effectiveness of restoration under different rates of missing data

4.2. Chaotic characterization of traffic flow

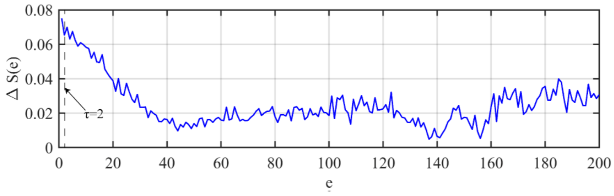
In this paper, valid data (a total of 7,775 sets of traffic data) that have been repaired and processed are used as test data for the determination of chaotic properties and phase space reconstruction.

4.2.1. Three-parameter determination of chaotic properties

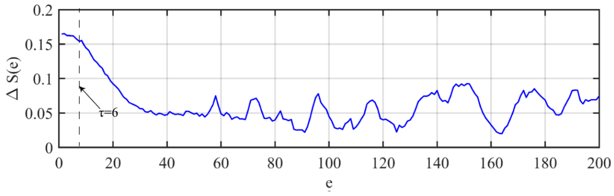
Since the selected valid data contains three variables: traffic volume, average speed and average occupancy rate, the valid data is firstly organized into the time series form, i.e, $\{x(n), n = 1,2,\ldots,7775\}$, for better chaotic characterization. Then, the delay time parameter of the



(a) Traffic volume



(b) Average location speeds



(c) Lane occupancy rate

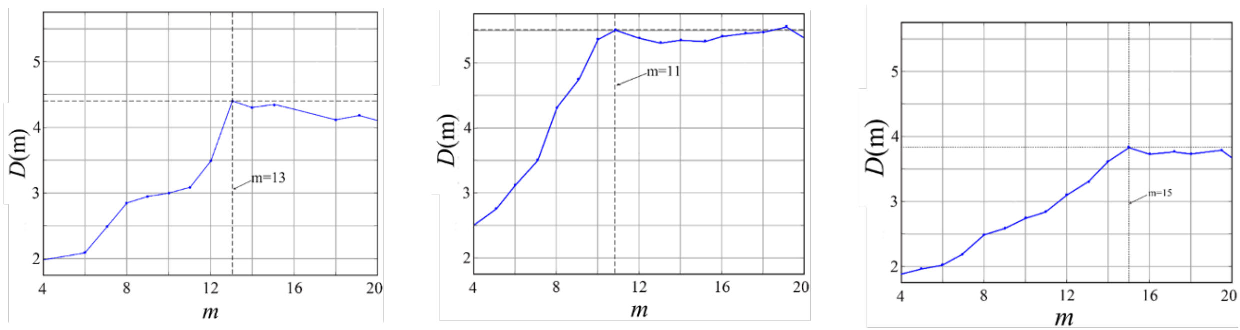
Fig. 7. $\overline{\Delta S}(e)$ curves for three parameters

time series is calculated according to the C-C algorithm, and the optimal delay time is taken as the first local minima of the $\overline{\Delta S}(e)$ curve [38]. The curve for the three parameters is shown in Fig. 7.

From Fig. 7, the first minima of the three parameters $\overline{\Delta S}(e)$-curves are $\tau = 7$, $\tau = 8$ and $\tau = 9$, respectively, which gives the delay times of the three-parameter time series as $\tau = 7$, $\tau = 8$ and $\tau = 9$, respectively. According to the G-P algorithm, a line graph of the three parameters correlation dimension with the embedding dimension can be obtained, as shown in Fig. 8.

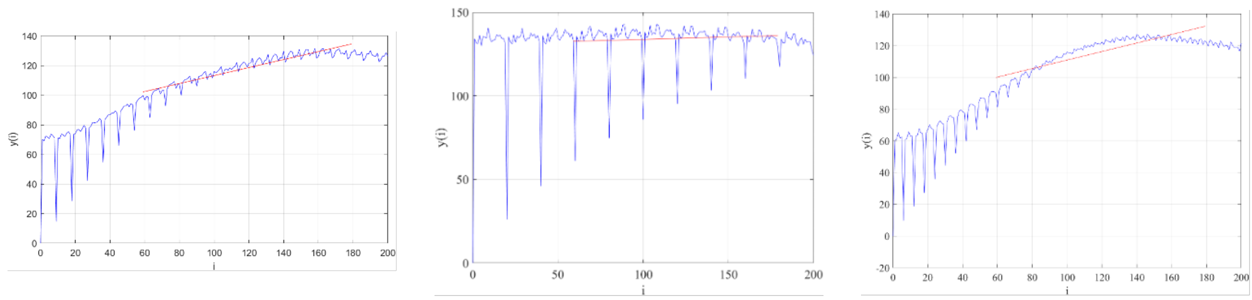
From Fig. 8, it can be seen that D(m) of the three-parameter time series grows with the increase of m. At the moment when m is 13, 11 and 15 respectively, D(m) is close to saturation, so the embedding dimensions are 13, 11 and 15 respectively.

In order to further determine the chaotic properties of the three-parameter time series, the maximum Lyapunov exponent of the series after phase space reconstruction is calculated using the small data volume method [39], and the results are shown in Fig. 9. The red straight line is the regression line fitted by the least squares method, and the slope of this line is the maximum Lyapunov exponent of the



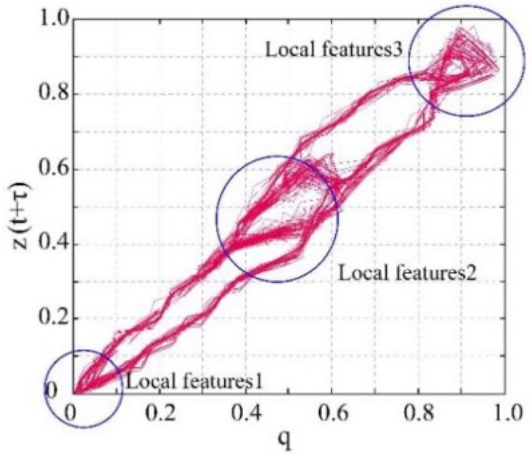
(a) Traffic volume (b) Average location speeds (c) Lane occupancy rate

Fig. 8. D(m) curves for three parameters.

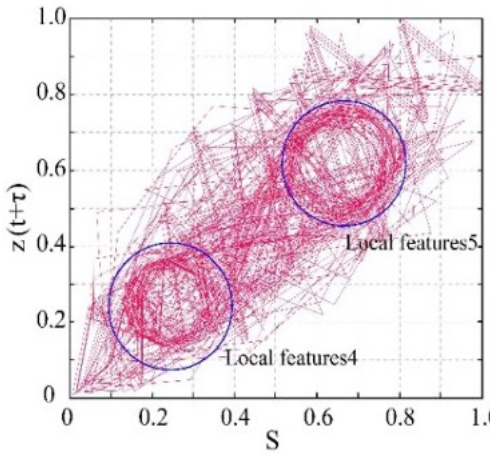


(a) Traffic volume (b) Average location speeds (c) Lane occupancy rate

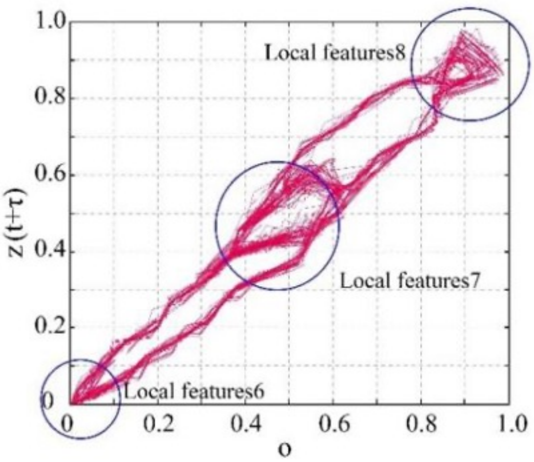
Fig. 9. Maximum Lyapunov exponents curves for three parameters.



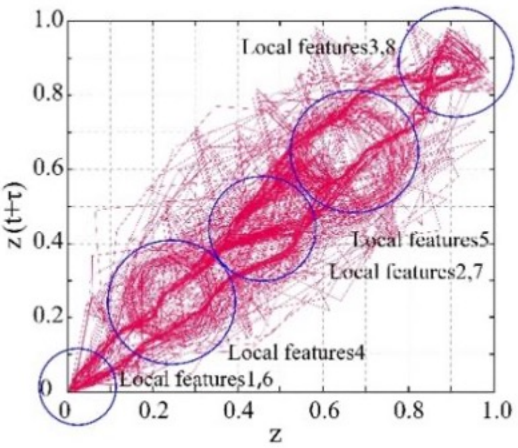
(a) traffic volume



(b) average speed



(c) average occupancy rate



(d) three-parameter fusion

Fig. 10. Phase space reconstruction of chaotic attractors based on multi-parameter fusion.

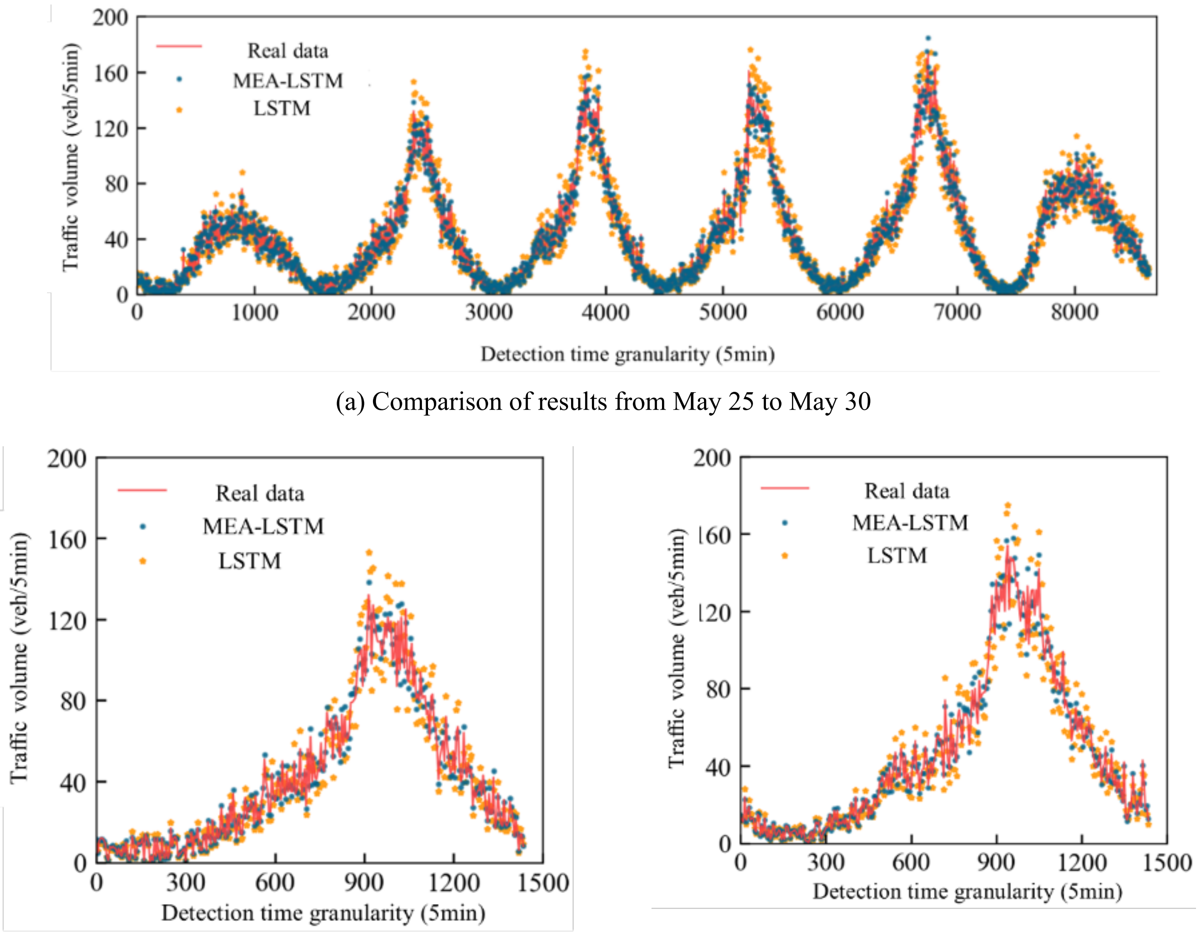
sequence. The maximum Lyapunov exponents of the three-parameter time series after phase space reconstruction are 0.2642, 0.0283 and 0.2615, respectively, and all of them are greater than 0, which proves that the series is a chaotic system.

4.2.2. Three-parameter time series phase space fusion

In order to obtain multi-parameter fused traffic flow data, the three-parameter sequences are reconstructed in the same dimension of the phase space using the phase space reconstruction technique. According to Takens' embedding theorem, sequences with chaotic properties can all characterize a more complete phase space structure of the original system when the appropriate delay time and embedding dimension are chosen. Therefore, phase space reconstruction of three-parameter sequences in the same high-dimensional space firstly needs to normalize the three sequences and determine the embedding dimension m. As shown in Fig. 8, all three sequences are essentially saturated at an embedding dimension of 11. Therefore, it is determined that m = 11. Based on the embedding window width solved by the C-C algorithm, the opti-

Table 2. Traffic flow time series phase space reconstruction parameters.

Traffic flow parameter	Delay time	Embedding dimension
Traffic volume	9	11
Average speed	7	11
Average occupancy rate	6	11



(a) Comparison of results from May 25 to May 30

(b) Comparison of results on May 26

(c) Comparison of results on May 27

Fig. 11. Comparison of model prediction results

mal delay time is inverted according to $\tau_w = (m-1)\tau$. After calculation, the traffic flow parameters phase space reconstruction parameters are shown in Table 2.

The three-parameter phase space reconstruction vectors are reconstructed into a high-dimensional phase space of the same dimension, and the Bayesian estimation theory is applied in this high-dimensional space to realize the fusion of the phase points, and a traffic flow data matrix containing more complete feature information is obtained, and the chaotic attractor of this chaotic system is shown in Fig. 10.

As can be seen from Fig. 10, the region of chaotic attractors in the aggregation state is a local feature of the sequence. The chaotic attractor representation maps of the traffic volume and occupancy time series in the traffic flow parameters are to some extent similar, showing three local features, but the chaotic attractor of the average speed time series is different from the first two variables, which also indicates that only using a single variable for phase space reconstruction and traffic flow prediction cannot represent all the characteristics of traffic flow chaotic system, and the prediction accuracy is low. After the fusion of multiple variables in high-dimensional phase space using Bayesian estimation theory, the local characteristics of chaotic attractors of multiple variables are reflected. It shows that after multivariate time series attractor fusion, the fused phase space information contains all the important characteristics of the measured traffic flow data.

The multi-parameter fusion technique proposed in this paper can not only show all the original main features of traffic flow as a dynamical system, but also show the characteristic information of traffic flow parameters in a more comprehensive way than the reconstruction information that can be achieved by a single variable. In the subsequent traffic flow prediction, the application of the data that have undergone multi-parameter phase space fusion to comprehensively consider multiple main features is very favorable to improve the prediction accuracy.

4.3. Traffic flow prediction results based on MEA-LSTM model

The prediction results and prediction errors of the LSTM model and the MEA-LSTM model are shown in Fig. 11 and Table 3.

Combined with Fig. 11 and Table 3, the comparative analysis shows that the fitting degree of the MEA-LSTM model is better than the LSTM model in terms of prediction accuracy, and each evaluation indicator has been optimized, including RMSE index decreased by 2.271, MEA index decreased by 3.096, MAPE index decreased by 3.61 %. It can be seen that the prediction accuracy of the LSTM model optimized by MEA has improved over the single LSTM model, indicating that the MEA-LSTM model proposed in this paper is feasible in the practical application of traffic flow prediction. In terms of prediction speed, the prediction time of the LSTM model is 14.5 min, while that of the MEA-LSTM model is 4.7 min, which is 3.1 times higher. Comprehensive analysis of the experimental results, and the reasons for improving the accuracy and prediction speed of the MEA-LSTM model are as follows: 1) The MEA model can carry out the search process for the optimal solution from multiple populations as well as multiple elements simultaneously, thus improving the search efficiency of the model and giving the model a faster convergence rate. 2) The combination of the MEA model with the LSTM model introduces an optimization-preserving property, where its optimal individuals are preserved after each iteration, ensuring that the run results are all closer to the optimal solution than the previous layer of the model. 3) As the number of iterations increases, the training error of the MEA-LSTM model varies more and more, which indicates that it will always be more efficient in solving the optimal parameters towards the global optimum.

5. Conclusions

The paper first proposes the NSDAE method to repair traffic data and compares it with various other data repair methods to highlight its effectiveness. Meanwhile, an improved LSTM prediction method is constructed based on the MEA by combining the advantages of the MEA and the LSTM model. The main findings are as follows.

(1) In this paper, we propose the NSDAE method to repair the original traffic flow data and compare its performance with other methods to determine the advantages of NSDAE. Through this method, effective data for making short-term traffic flow predictions were obtained.

(2) Considering that it is difficult to comprehensively characterize the traffic flow using univariate data for prediction, this paper firstly determines the chaotic characteristics of the traffic flow using the chaos theory determination method, analyses the similarities and differences among the three parameters, and finds out their important features. Then, according to the determination results, the Bayesian estimation method is selected to reconstruct the phase space of the three parameters, so that the traffic flow parameters are reconstructed into one-dimensional data, and can represent the data characteristics of the three parameters. Reconstructing the multi-dimensional data phase space into one-dimensional data provides a data basis for the establishment of the short-time traffic flow prediction model, and also reduces the computational cost of the model.

(3) In this paper, we take advantage of the fact that the MEA can divide the data into several subpopulations for optimal search, and perform convergence and dissimilation operations alternately, so that the weights and thresholds of the prediction model can be optimized quickly, and then propose the MEA-LSTM model. The MEA-LSTM model proposed in this paper improves the prediction accuracy, computational efficiency, and generalization ability, and can provide a reference basis for related research.

Acknowledgments

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Table 3. Prediction errors of the LSTM model and the MEA-LSTM model.

Evaluation indicators	LSTM model	MEA-LSTM model
RMSE	9.332	7.061
MAE	10.682	7.586
MAPE	11.842%	8.232%

to express their sincere appreciation to the aforementioned organizations.

Declaration of Competing Interest

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

References

1. Lv Y, Duan Y, Kang W, et al. Traffic flow prediction with big data: A deep learning approach. IEEE transactions on intelligent transportation systems, 2014, 16(2): 865-873.
2. Shu W, Cai K, Xiong N N. A short-term traffic flow prediction model based on an improved gate recurrent unit neural network. IEEE Transactions on Intelligent Transportation Systems, 2021, 23(9): 16654-16665.
3. Hou Q, Leng J, Ma G, et al. An adaptive hybrid model for short-term urban traffic flow prediction. Physica A: Statistical Mechanics and its Applications, 2019, 527: 121065.
4. Chen C, Liu Z, Wan S, et al. Traffic flow prediction based on deep learning in internet of vehicles. IEEE transactions on intelligent transportation systems, 2020, 22(6): 3776-3789.
5. Miglani A, Kumar N. Deep learning models for traffic flow prediction in autonomous vehicles: A review, solutions, and challenges. Vehicular Communications, 2019, 20: 100184.
6. Tian Y, Pan L. Predicting short-term traffic flow by long short-term memory recurrent neural network// 2015 IEEE international conference on smart city. IEEE, 2015: 153-158.
7. Sun Z, Hu Y, Li W, et al. Prediction model for short-term traffic flow based on a K-means-gated recurrent unit combination. IET Intelligent Transport Systems, 2022, 16(5): 675-690.
8. Peng H, Wang H, Du B, et al. Spatial temporal incidence dynamic graph neural networks for traffic flow forecasting. Information Sciences, 2020, 521: 277-290.
9. Lu Z, Lv W, Cao Y, et al. LSTM variants meet graph neural networks for road speed prediction. Neurocomputing, 2020, 400: 34-45.
10. Yang B, Sun S, Li J, et al. Traffic flow prediction using LSTM with feature enhancement. Neurocomputing, 2019, 332: 320-327.
11. Wei W, Wu H, Ma H. An autoencoder and LSTM-based traffic flow prediction method. Sensors, 2019, 19(13): 2946.
12. Zhao Z, Chen W, Wu X, et al. LSTM network: a deep learning approach for short-term traffic forecast. IET intelligent transport systems, 2017, 11(2): 68-75.
13. Abadi A, Rajabioun T, Ioannou P A. Traffic flow prediction for road transportation networks with limited traffic data. IEEE transactions on intelligent transportation systems, 2014, 16(2): 653-662.
14. Xiao Y, Yin Y. Hybrid LSTM neural network for short-term traffic flow prediction. Information, 2019, 10(3): 105.
15. Ma Q, Huang G H, Ullah S. A multi-parameter chaotic fusion approach for traffic flow forecasting. IEEE Access, 2020, 8: 222774-222781.
16. Hong W C. Traffic flow forecasting by seasonal SVR with chaotic simulated annealing algorithm. Neurocomputing, 2011, 74(12-13): 2096-2107.
17. Cheng A, Jiang X, Li Y, et al. Multiple sources and multiple measures-based traffic flow prediction using the chaos theory and support vector regression method. Physica A: Statistical Mechanics and its Applications, 2017, 466: 422-434.
18. Tang J, Zeng J, Wang Y, et al. Traffic flow prediction on urban road network based on license plate recognition data: combining attention-LSTM with genetic algorithm. Transportmetrica A: Transport Science, 2021, 17(4): 1217-1243.
19. Cai L, Lei M, Zhang S, et al. A noise-immune LSTM network for short-term traffic flow forecasting. Chaos: An Interdisciplinary Journal of Nonlinear Science, 2020, 30(2).
20. Li P, Dong B, Li S, et al. A repair method for missing traffic data based on FCM, optimized by the twice grid optimization and sparrow search algorithms. Sensors, 2022, 22(11): 4304.
21. Li J, Li R, Xu L. Multi-stage deep residual collaboration learning framework for complex spatial–temporal traffic data imputation. Applied Soft Computing, 2023, 147: 110814.
22. Liu X, Zhang H, Niu Y, et al. Modeling of an ultra-supercritical boiler-turbine system with stacked denoising auto-encoder and long short-term memory network. Information Sciences, 2020, 525: 134-152.
23. Mohanty H, Roudsari A H, Lashkari A H. Robust stacking ensemble model for darknet traffic classification under adversarial settings. Computers & Security, 2022, 120: 102830.
24. Young L S. Mathematical theory of Lyapunov exponents. Journal of Physics A: Mathematical and Theoretical, 2013, 46(25): 254001.
25. Sahoo S, Roy B K. Design of multi-wing chaotic systems with higher largest Lyapunov exponent. Chaos, Solitons & Fractals, 2022, 157: 111926.
26. Ghorbani M A, Kisi O, Aalinezhad M. A probe into the chaotic nature of daily streamflow time series by correlation dimension and largest Lyapunov methods. Applied Mathematical Modelling, 2010, 34(12): 4050-4057.
27. Ghorbani M A, Khatibi R, Mehr A D, et al. Chaos-based multigene genetic programming: A new hybrid strategy for river flow forecasting. Journal of hydrology, 2018, 562: 455-467.
28. Jiang J J, Zhang Y, McGilligan C. Chaos in voice, from modeling to measurement. Journal of Voice, 2006, 20(1): 2-17.

29. Takens F. The reconstruction theorem for endomorphisms. Bulletin of the Brazilian Mathematical Society, 2002, 33: 231-262.
30. Noakes L. The Takens embedding theorem. International Journal of Bifurcation and Chaos, 1991, 1(04): 867-872.
31. Bosq D, Ruiz-Medina M D. Bayesian estimation in a high dimensional parameter framework. 2014.
32. Bai H, Cao Q, An S. Mind evolutionary algorithm optimization in the prediction of satellite clock bias using the back propagation neural network. Scientific Reports, 2023, 13(1): 2095.
33. Liu H, Tian H, Liang X, et al. New wind speed forecasting approaches using fast ensemble empirical model decomposition, genetic algorithm, Mind Evolutionary Algorithm and Artificial Neural Networks. Renewable Energy, 2015, 83: 1066-1075.
34. Sayed S A, Abdel-Hamid Y, Hefny H A. Artificial intelligence-based traffic flow prediction: a comprehensive review. Journal of Electrical Systems and Information Technology, 2023, 10(1): 13.
35. Tian Y, Zhang K, Li J, et al. LSTM-based traffic flow prediction with missing data. Neurocomputing, 2018, 318: 297-305.
36. Lee C, Ryu T, Kim H, et al. Efficient approach of sliding window-based high average-utility pattern mining with list structures. Knowledge-Based Systems, 2022, 256: 109702.
37. Kai Z, Jinchun S, Ke N, et al. Lagrange interpolation learning particle swarm optimization. PloS one, 2016, 11(4): e0154191.
38. Said A, Abbasi R A, Maqbool O, et al. CC-GA: A clustering coefficient based genetic algorithm for detecting communities in social networks. Applied Soft Computing, 2018, 63: 59-70.
39. Rosenstein M T, Collins J J, De Luca C J. A practical method for calculating largest Lyapunov exponents from small data sets. Physica D: Nonlinear Phenomena, 1993, 65(1-2): 117-134.

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Shrinkage and Expansion Mechanisms of Resource-based Cities: Analysis Based on Multidimensional Typology Definition Matrix

Xianjian Yi [a], Lei Wang [b], Xinyue Gu [c,*]

[a] Department of Geography and Resource Management, The Chinese University of Hong Kong, Hong Kong SAR, China
[b] School of Architecture, Tianjin University, Tianjin, China.
[c] Department of Land Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong SAR, China

K E Y W O R D S

urban shrinkage,
random forest,
resource-based cities

A B S T R A C T

The urban shrinkage phenomenon is increasingly common. However, at the same time, it is accompanied by local growth within the region, and its complex impact mechanism still lacks in-depth research. This paper takes Daqing, a resource-based city, as an example and constructs a multi-dimensional urban growth/shrinkage type definition matrix. The random forest classification model is used to quantitatively analyze the relevant factors affecting the classification matrix by comparing different models. The results show that: (1) The growth/shrinkage of Daqing City leads to a concentric structure of intensive growth—expansion growth—expansion shrinkage—intensive shrinkage that gradually changes from the center to the periphery in space. (2) The random forest classification model can better explain the cause mechanism of urban growth/shrinkage. (3) The growth/shrinkage of resource-based cities in the transformation stage is mainly affected by economic factors, such as traffic accessibility and urban morphology related to the resource economy. This study provides an evaluation framework from qualitative to quantitative, providing useful references for research and planning policy formulation in related fields.

40.Introduction

Urban shrinkage is a phenomenon that is becoming increasingly common, characterized by population loss, which first appeared at the end of the last century. With the development of globalization, the problems involved in urban shrinkage, such as inefficient land use, economic recession, etc., have become more complex and widespread (Shan et al., 2025; Shan & Gu, 2024). Moreover, urban shrinkage is gradually considered an inevitable outcome of the later stage of urban development (Bartholomae et al., 2017). Therefore, urban shrinkage has attracted widespread attention from scholars as a global phenomenon.

The definition of urban shrinkage is still controversial. Initially, people used population loss to judge whether a city was shrinking (Döringer et al., 2020). In recent years, the research on urban shrinkage has developed into a multi-dimensional perspective, and factors such as population, economy, and space are used to reflect the degree and type of urban shrinkage (Mallach et al., 2017). The classification method of urban shrinkage based on multi-dimensional definition further deepens the identification of urban shrinkage. Gao et al. classified shrinking cities by arranging and combining

* Corresponding author at: Department of Land Surveying and Geo-informatics, The Hong Kong Polytechnic University, Hong Kong SAR, China
E-mail address: xinyue.gu@connect.polyu.hk (Xinyue Gu).

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the measurement results of three dimensions: population, economy, and land use (Gao et al., 2021). Kim et al. refined the classification of shrinking cities in Korea by improving the traditional classification matrix of population and economy (Kim et al., 2022). The distilled research based on a category also provides more powerful support for discussing relevant impact mechanisms and formulating targeted policies.

Regarding relevant impact mechanisms, shrinking cities in different countries and regions have other main causes and characteristics. Shrinkage in Western countries mainly occurs in heavy industrial areas, and its main reasons are globalization, deindustrialization, and resource depletion. In Japan, factors such as aging and low fertility are the main factors leading to urban shrinkage (Döringer et al., 2020). In China, economic factors are important factors affecting shrinking cities (*Shrinking Cities in a Rapidly Urbanizing China - Ying Long, Kang Wu, 2016*). Therefore, when studying urban shrinkage in China, we must focus on economic factors, such as industrial transformation and economic structure adjustment. In addition, the continuous development of big data and computer technology provides more choices and possibilities for the research methods of relevant impact mechanisms. More sources and higher precision big data can be used to reflect and analyze urban shrinkage. For example, night light data can reflect the economic activity intensity and vitality of different locations in the same area from the perspective of spatial distribution. They thus can be used to study urban shrinkage (Jiang et al., 2020). The advancement of computer technology has also promoted the development and innovation of quantitative research methods. Empirical models such as the OLS and GWR models explore the linear correlation (Deng & Ma, 2015) and spatial distribution mechanism of urban shrinkage-related problems, respectively (Guan et al., 2021). In recent studies, nonlinear models have been used to explore the nonlinear relationship between the single measurement dimension of shrinking cities and possible related influencing factors (Peng et al., 2023), providing a new perspective for urban shrinkage research.

The current research on urban shrinkage mainly focuses on the definition and identification, cause mechanism, and other aspects of urban shrinkage. Although there are many studies on shrinking cities, due to the complexity of its agent, there is also local urban growth while shrinking. We also found some research perspectives and problems that need to be fully explored from the relevant research: (1) The multi-dimensional definition of shrinking cities based on classification types only qualitatively explains the classification causes and mechanisms through case analysis, lacking quantitative research. (2) The nonlinear relationship between the influencing factors of shrinking cities based on classification machine learning models still needs to be improved in research. (3) The coupling relationship between shrinkage and growth under the transformation of resource-based cities has yet to be discussed in detail. Therefore, based on these problems, this study conducts relevant research, taking Daqing, a typical resource-based city, as the research object, and explores the spatial distribution of urban growth and shrinkage types under the multi-dimensional definition from the perspective of resource-based city transformation. In addition, we also compare the interpretability and nonlinear relationship of different machine learning classification models for relevant influencing factors. This study aims to provide a comprehensive research framework from type evaluation to quantitative analysis of appropriate mechanisms. Based on this framework, we conduct in-depth research on the mechanism of shrinking cities under the background of resource-based city transformation.

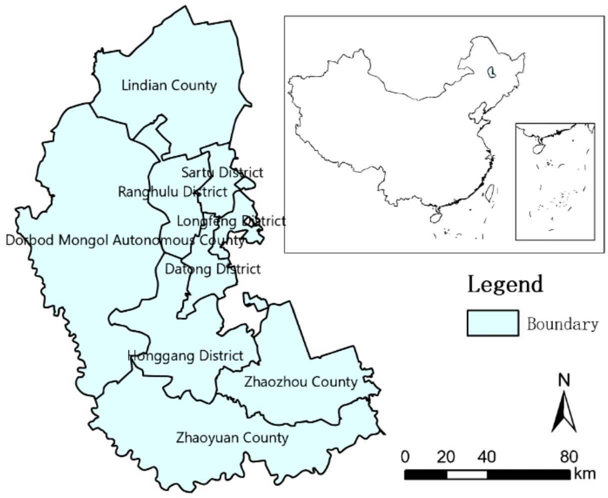

Fig. 1. Regions of Daqing City.

41.Materials and Methods

41.1.Study Area and Data

As shown in Fig. 1, this study takes Daqing City, Heilongjiang Province, Northeast China, as the research object, and the research period is 2015-2020. As an important resource-based city in China, Daqing faces problems such as ecological environment damage, complex social contradictions, industrial system transformation, resource depletion dilemma, etc. In recent years, it has continuously controlled the exploitation of oil and gas resources and explored new directions for industrial change. Since 2015, the output of Daqing Oilfield has begun to decline, with an average annual reduction of more than 1.3 million tons during the “13th Five-Year Plan” period. Daqing's urban and population structures based on primary oil development also face reorganization in the transition stage to adapt to industrial diversification. Daqing's special development stage also causes urban shrinkage and growth to coexist. This study aims to quantitatively identify and describe the characteristics of urban shrinkage in Daqing from 2015 to 2020 and analyze its cause mechanism.

This study collects and organizes data on the spatial pattern of urban growth and shrinkage subtypes and related possible influencing factors. To improve the research accuracy, this paper abandons panel data. It selects grid data with spatial resolution ≤1km for relevant research and classifies them according to type measurement and relevant influencing factors. All data are summarized in Table 1.

Among them, Population Density (PD) represents the population per km², reflecting the characteristics of population spatial distribution. Night-light data (NL) can reflect the intensity of economic activity, electricity consumption, and other energy consumption indicators, thus characterizing economic vitality. Artificial Impervious Areas (AIA) reflect the built-up area, thus reflecting the overall land use situation. Regarding relevant influencing factors, we explore the specific impacts from different perspectives, such as population age structure, economic level, land use subdivision data, etc. Among them, GDP reflects the specific economic output of each grid; AR and BR reflect the impact of population age structure; RD reflects traffic accessibility; and UL, RS, and OCL, respectively, represent the use of urban, rural, and special land. We use different normalization methods to process data and compare and select the better normalization method to eliminate the dimension difference.

41.2.Urban growth/shrinkage based on multi-dimensional definition

This study establishes a matrix of urban growth/shrinkage type definition based on three dimensions: population, economy, and land use, according to the Chinese context, to determine the subtypes of urban growth and shrinkage. First, we overlay the population density data and night light data of each grid to construct a comprehensive economic vitality (EV) indicator, which represented equation (1).

$$EV = DN \times PD \tag{1}$$

Where EV is the economic vitality index of each grid, DN is the night light intensity value, and PD is each grid's population number. A data overlay can avoid the brightness anomalies caused by high-brightness economic activities such as fishing and natural disasters such as fires and truly reflect the economic vitality.

Then, we construct the x-axis and y-axis by the positive and negative of the comprehensive EV index and land use index (AIA) and build a discrimination matrix of growth and shrinkage at the grid scale by the four-quadrant classification method (Table 2). The matrix divides the growth and shrinkage situation into four different spatial types,

Table 1. Multi-source data being applied

Application	Name	Sources
Type determination	Population Density (PD)	WorldPop (https://hub.worldpop.org/)
	Nighttime Light (NL)	(A Harmonized Global Nighttime Light Dataset 1992–2018 | Scientific Data, n.d.)
	Artificial Impervious Areas (AIA)	(Li et al., 2020)
Analyze Impact factors	GDP	(Zhao et al., 2017)
	Aging Rate (AR)	WorldPop (https://hub.worldpop.org/)
	Birth Rate (BR)	
	Road Density (RD)	https://www.openstreetmap.org
	Urban Land (UL)	https://www.resdc.cn
	Rural Settlements (RS)	
	Other Construction Land (OCL)	

and the four quadrants correspond to expansion growth, intensive growth, expansion shrinkage, and intensive shrinkage, respectively.

41.3.Multi-model comparison and selection and influencing factor analysis

This study first tests the multicollinearity between variables by Pearson correlation analysis and eliminates variables with high data correlation with 0.8 as the standard (Wilcox, 2009). Then, we explore the nonlinear relationship between classification types and relevant influencing factors by machine learning algorithms. Since there is no conclusive conclusion on the fitting effect of different models on type determination, we conducted a multi-model comparison analysis. Regarding the specific classification model selection, we chose several machine learning models such as random forest, xgboost, logistic regression, K-nearest neighbor (KNN), and support vector machine (SVM) from two perspectives of mainstream models and newer models. Then, we construct an 80% training set and 20% test set for each model and comprehensively compare each model's accuracy, recall, precision, F1 value, and other indicators to judge the fitting effect and interpretability (Goutte & Gaussier, 2005). Finally, based on the selected machine learning algorithm with a better comprehensive outcome, we further analyze the specific impact mechanism of relevant influencing factors on urban growth and shrinkage according to the indicator results, such as feature importance generated by the algorithm.

42.Results & Discussion

42.1.Spatial distribution of growth and shrinkage types in Daqing City

Through data analysis, we obtained the overall characteristics of urban development in Daqing City from 2015 to 2020 (Fig. 2), that is, dominated by intensive shrinkage space, accompanied by perforated intensive growth and expansion shrinkage space, and there are also local scattered growth spaces in the intensive growth space area. Specifically, 12046 grids show intensive shrinkage, 5800 grids show intensive growth, 2503 grids show expansion shrinkage, and 1411 grids show expansion growth. From the perspective of urban overall spatial distribution, intensive shrinkage is mainly distributed in the urban periphery areas of Lindian County, Dorbod Mongolian Autonomous County, Datong, Zhao Yuan, and other regions of the north, west, and south of the city. Intensive growth and expansion growth are mainly distributed in the core urban areas of Sartu, Longfeng, Honggang, Ranghulu, and other regions of the central and eastern parts of the city and Zhaozhou area in the southeast, as well as local scattered regions of the periphery urban areas. Expansion shrinkage is mainly scattered in Daqing's northwest and southeast regions, forming a concentric structure of intensive growth-expan-

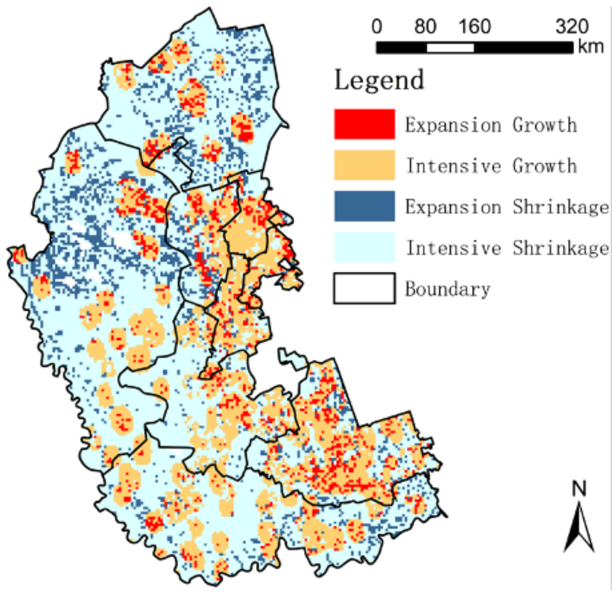

Fig. 2. Spatial Distribution of Urban Shrinkage/Expansion Types in Daqing City from 2015 to 2020

Table 2. Identification matrix of urban growth / shrinkage

Economic Vitality (EV)		Built-up Areas (AIA)		Space Type
Relative Relation	Type	Relative Relation	Type	
$R_{EV}>0$	Growth	$R_{AIA}>0$	Expansion	Expansion growth
		$R_{AIA}\leq0$	Intensive	Intensive growth
$R_{EV}\leq0$	Shrinkage	$R_{AIA}>0$	Expansion	Expansion shrinkage
		$R_{AIA}\leq0$	Intensive	Intensive shrinkage

Fig. 3. Correlation Matrix of Influencing Factors Related to Urban Shrinkage from 2015 to 2020.

sion shrinkage-intensive shrinkage that gradually changes from the center to the periphery.

42.2.Collinearity and multi-model comparison

As shown in Fig. 3, we first tested the collinearity between variables by Pearson correlation analysis. According to the results, except for AR and BR, the absolute values of correlation coefficients between other variables are all less than 0.2, meaning there is almost no multicollinearity problem between variables.

BR and AR have a collinearity overlap problem because they reflect population structure characteristics and come from the same data set. We eliminate variable BR and use the remaining variables as influencing factors for further analysis.

Then, this study compares different machine learning models and selects the model with a better comprehensive analysis of the effect on the urban growth/shrinkage classification problem and its relevant influencing factors. As shown in Table Ⅲ, we comprehensively compare the evaluation results of models such as logistic regression, random forest, xgboost, KNN, SVM, etc. From the perspective of preventing overfitting, the logistic regression model, random forest model, and SVM model perform better, with the difference between the training set and test set within 0.02, while the difference between the training set and test set of the other two models are more than 0.1. Among them, the best-performing model is the random forest model, with the difference between the training set and test set Accuracy, Recall, Precision, and F1 values within

Table 3. Comparison of Evaluation Results of Different Classification Models

Machine Learning Model		Model Evaluation Results			
		Accuracy	Recall	Precision	F1
Logistic Regression	Train	0.587	0.587	0.466	0.507
	Test	0.572	0.572	0.451	0.49
Random Forest	Train	0.624	0.624	0.505	0.55
	Test	0.619	0.619	0.501	0.546
xgboost	Train	0.783	0.783	0.81	0.76
	Test	0.602	0.602	0.533	0.543
KNN	Train	0.679	0.679	0.662	0.663
	Test	0.533	0.533	0.496	0.511
SVM	Train	0.557	0.557	0.462	0.401
	Test	0.544	0.544	0.443	0.387

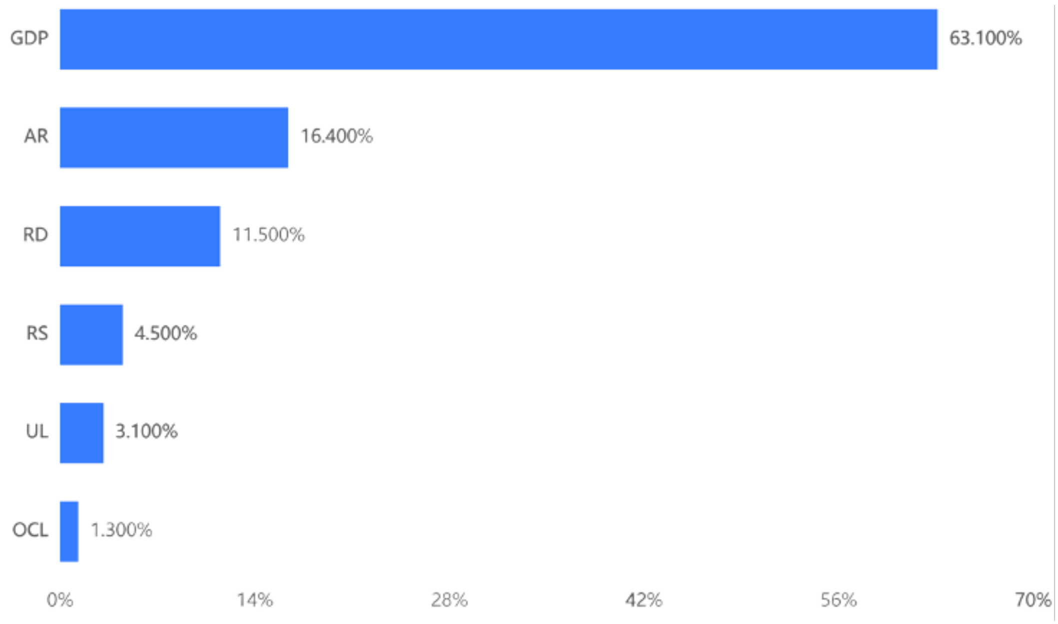

Fig. 4. Features importance of Influencing Factors Related to Urban Shrinkage from 2015 to 2020.

0.005 or 0.01, which is the smallest compared with other models. Based on this, we choose the model with the highest comprehensive evaluation score among the models with a good fitting degree. The model with the highest overall score is also a random forest model, with its training set and test set Accuracy, Recall > 0.6, Precision, and F1 values > 0.5 are the highest compared with other models. Therefore, we choose the random forest model to analyze influencing factors further.

42.3.Resource-based city influencing factor analysis based on random forest classification model

As shown in Fig. 4, the feature importance chart generated by the random forest model shows the degree of influence of different influencing factors on urban shrinkage/growth. Among them, the GDP score accounts for more than 60%, the main influencing factor, while AR and RD's feature importance exceeds 10%, respectively, which has a certain impact. The scores of the three land use modes are low, and the related effects are small. By comparison, economic factors dominate urban growth/shrinkage in Chinese resource-based cities. At the same time, traffic accessibility and population structure also promote or inhibit urban growth/shrinkage to a certain extent. This reflects the current situation faced by resource-based towns in China, that is, the impact of the original urban pattern and traffic network based on resource exploitation on industrial transformation and economic development. Daqing City, as a typical resource-based city formed and grew with the development of oil fields and oil field economy, has a development mode of "city-mine integration." Its urban and rural distribution is sparse and uneven, with dense urban areas and light peripheral counties.

In addition, its original urban spatial distribution is based on the exploitation and transportation of oil and gas resources, that is, relying on the construction of traffic trunk lines and extending along them, forming a city shape with traffic trunk lines as the axis, and the core old urban area and the railway transportation intensive eastern area highly overlap. However, the distribution of resources leads to a loose connection between different metropolitan areas; each region has its system, showing a dispersed multi-center group structure. Generally speaking, this urban structure pattern cannot meet the needs of urban transformation and development. The overly dispersed urban layout pattern is not conducive to forming a regional center with strong attraction and radiation force. It is not conducive to transforming urban economic development from extensive to intensive. According to specific analysis types, scattered regional centers attract market, population, and other elements flow and aggregation by relying on oil field resources.

In the stage of urban industrial transformation, they change from large-scale expansion growth to intensive growth combined with local expansion growth to reduce resource consumption and dependence and optimize the existing resource industry mode. These areas spread from the eastern core urban area to other directions, showing a radiative scattered distribution. The peripheral regions of scattered centers show an intensive shrinkage pattern, which replaces inefficient stock and redundant space with retreatment and smooths over the economic transformation stage. Expansion shrinkage-type scattered areas are mostly located in the northern part of Daqing City, which is also the main traffic line away from the main urban area side area. The main reason is that there is a mismatch between the government's strategic advancement policy and the actual market element flow in the stage of transformation and development, resulting in excessive spatial supply and an imbalance of population and economic structure. At the same time, due to the exploration of new industries and the consumption of original resources leading to the downturn of the actual industry economy, the city's development expectation decreases. This leads to the outflow of labor population and local population aggregation, reflecting the population structure change represented by a high aging rate.

43.Conclusions

This study establishes an identification framework for urban growth and shrinkage from population, economy, and land use. It compares different machine learning models to explore the degree and mechanism of influence of relevant influencing factors under the context of resource-based city transformation from 2015 to 2020. The research results are: (1) Daqing City is dominated by intensive shrinkage space, accompanied by perforated intensive growth and expansion shrinkage space. At the same time, there are local scattered expansion growth spaces in the intensive growth space area, forming a concentric structure of intensive growth—expansion growth—expansion shrinkage—intensive shrinkage that gradually changes from the center to the periphery. (2) Compared with other models, the random forest classification model has better interpretability for urban growth/shrinkage type influencing factor analysis. (3) Economic factors are the main factors leading to urban growth/shrinkage in Chinese resource-based cities, such as traffic accessibility and urban layout determined by the resource economy. In summary, by providing a comprehensive research framework from type evaluation to quantitative analysis of relevant mechanisms, this study can provide useful supplements for urban shrinkage-related research based on type evaluation and applicable sustainable planning policy formulation.

References

1. *A harmonized global nighttime light dataset 1992–2018 | Scientific Data*. (n.d.). Retrieved October 1, 2023, from https://www.nature.com/articles/s41597-020-0510-y
2. Bartholomae F., Woon Nam C., & Schoenberg A. (2017). Urban shrinkage and resurgence in Germany. *Urban Studies*, *54*(12), 2701–2718. https://doi.org/10.1177/0042098016657780
3. Deng, C., & Ma, J. (2015). Viewing urban decay from the sky: A multi-scale analysis of residential vacancy in a shrinking U.S. city. *Landscape and Urban Planning*, *141*, 88–99. https://doi.org/10.1016/j.landurbplan.2015.05.002
4. Döringer, S., Uchiyama, Y., Penker, M., & Kohsaka, R. (2020). A meta-analysis of shrinking cities in Europe and Japan. Towards an integrative research agenda. *European Planning Studies*, *28*(9), 1693–1712. https://doi.org/10.1080/09654313.2019.1604635
5. Gao, Z., Wang, S., & Gu, J. (2021). Identification and Mechanisms of Regional Urban Shrinkage: A Case Study of Wuhan City in the Heart of Rapidly Growing China. *Journal of Urban Planning and Development*, *147*(1), 05020033. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000643
6. Goutte, C., & Gaussier, E. (2005). A Probabilistic Interpretation of Precision, Recall and F-Score, with Implication for Evaluation. In D. E. Losada & J. M. Fernández-Luna (Eds.), *Advances in Information Retrieval* (pp. 345–359). Springer. https://doi.org/10.1007/978-3-540-31865-1_25
7. Guan, D., He, X., & Hu, X. (2021). Quantitative identification and evolution trend simulation of shrinking cities at the county scale, China. *Sustainable Cities and Society*, *65*, 102611. https://doi.org/10.1016/j.scs.2020.102611
8. Jiang, Z., Zhai, W., Meng, X., & Long, Y. (2020). Identifying Shrinking Cities with NPP-VIIRS Nightlight Data in China. *Journal of Urban Planning and Development*, *146*(4), 04020034. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000598
9. Kim Y. E., Lee J. S., & Kim S. (2022). Proposing the classification matrix for growing and shrinking cities: A case study of 228 districts in South Korea. *Habitat International*, *127*, 102644. https://doi.org/10.1016/j.habitatint.2022.102644
10. Li X., Gong P., Zhou Y., Wang J., Bai Y., Chen B., Hu T., Xiao Y., Xu B., Yang J., Liu X., Cai W., Huang H., Wu T., Wang X., Lin P., Li X., Chen J., He C., … Zhu Z. (2020). Mapping global urban boundaries from the global artificial impervious area (GAIA) data. *Environmental Research Letters*, *15*(9), 094044. https://doi.org/10.1088/1748-9326/ab9be3
11. Mallach, A., Haase, A., & Hattori, K. (2017). The shrinking city in comparative perspective: Contrasting dynamics and responses to urban shrinkage.

Cities, *69*, 102–108. https://doi.org/10.1016/j.cities.2016.09.008

12. Peng, W., Wu, Z., Duan, J., Gao, W., Wang, R., Fan, Z., & Liu, N. (2023). Identifying and quantizing the non-linear correlates of city shrinkage in Japan. *Cities*, *137*, 104292. https://doi.org/10.1016/j.cities.2023.104292
13. Shan, C., & Gu, X. (2024). Understanding urban sprawl based on open-source data: A study of three American cities. In *Urban Construction and Management Engineering IV*. CRC Press.
14. Shan, C., Liu, Y., & Gu, X. (2025). Curbing Urban Sprawl: A Study of Three Typical American Cities from the Perspectives of the Built Environment and Socioeconomics. *Journal of Urban Planning and Development*, *151*(1), 05024044. https://doi.org/10.1061/JUPDDM.UPENG-5316
15. *Shrinking cities in a rapidly urbanizing China—Ying Long, Kang Wu, 2016*. (n.d.). Retrieved September 30, 2023, from https://journals.sagepub.com/doi/full/10.1177/0308518X15621631
16. Wilcox, R. R. (2009). Comparing Pearson Correlations: Dealing with Heteroscedasticity and Nonnormality. *Communications in Statistics - Simulation and Computation*, *38*(10), 2220–2234. https://doi.org/10.1080/03610910903289151
17. Zhao, N., Liu, Y., Cao, G., Samson, E. L., & Zhang, J. (2017). Forecasting China's GDP at the pixel level using nighttime lights time series and population images. *GIScience & Remote Sensing*, *54*(3), 407–425. https://doi.org/10.1080/15481603.2016.1276705

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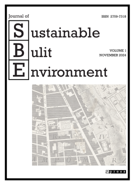

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How to Produce Cultural Space for Sustainable Development Towards Rural Revitalization: A Case Study of China

Haiyu Wang [a,*,†] , Changcan Li [a,†], Kunpeng Ai [a]

[a] *Institute for Public Policy and Social Administration Innovation, Henan Normal University,Xinxiang 453007, China*

KEYWORDS

rural cultural revitalization,
space production,
sustainable rural development

ABSTRACT

Cultural revitalization is a key factor in the sustainable development of the countryside and is included in the five-dimensional indicators of China's rural revitalization strategy. Although established studies have examined the spatial dimension of rural cultural revitalization, the internal structure of spatial production and the logic of action are still not entirely clear. Based on an interview survey in villages in northern Henan, China, this paper conducts a qualitative study of the structured characteristics of rural cultural spatial production and the actor logic behind it using a grounded theory research method. The results show that the production of local cultural space, socio-cultural space, mass recreational space, and cultural industries space constitute a composite structured rural cultural space. Public power, intellectual elites, residents' rights and industrial capital have demonstrated a “co-constructive” cooperative relationship This paper provides a theoretical and empirical basis for promoting rural cultural revitalization and sustainable development through the production of rural cultural space.

1. Introduction

In the era of industrial and technological civilization, sustainable rural development has become a hotspot and a focus of attention for governments and academics around the world, and is of great relevance to both developed and developing countries [1][2].As a major agricultural country in the world, China's strategies and actions in the field of sustainable rural development will have an important impact on the global governance of agriculture and rural areas. However, with the transformation of China's rural society, the changes in the rural social structure and cultural order have brought conflicts such as subjective crisis, weakening of values, and the impact of modernity to China's rural culture [3], which is not conducive to the sustainable development of rural culture. In the Chinese context, especially in official parlance, the scope of culture is relatively broad and typically encompasses excellent traditional culture, historically formed customs and habits, social ideology and morality, literature and art, and value systems, etc. In light of the actual circumstances in Chinese rural areas, this usually comprises customs and habits, cultural heritage, literary and artistic activities, and ideology and morality. The 19th National Congress of the Communist Party of China (CPC) proposed the

* Corresponding author at: Institute for Public Policy and Social Administration Innovation, Henan Normal University,Xinxiang 453007, China

E-mail address: wanghaiyu@stu.htu.edu.cn (Haiyu Wang)

† These authors contributed equally to this work.

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"Rural Revitalization Strategy" as a strategic arrangement for the sustainability of rural development. In this conference document, "prosperous industries, ecological livability, civilized rural customs, effective governance, and a rich life" were defined as the general requirements of the rural revitalization strategy. In October 2022, the twentieth national congress of the Communist Party of China (CPC) further explicitly proposed "accelerating the construction of a strong agricultural country, and solidly promoting the development of rural industry, talent, culture, ecology and organization." The Chinese government believes that sustainable development of rural areas depends on positive performance in these five dimensions of rural society. The practice of the countryside in the five dimensions of industry, talent, culture, ecology and organization has become a key indicator for measuring the sustainable development of the Chinese countryside. For the revitalization of rural culture, its indicators encompass the rejuvenation of rural historical and cultural traditions, the elevation of ideological and moral standards, the prosperity of residents' cultural life, and the level of cultural industrialization.[1] As the revitalization of rural culture gradually becomes part of the national strategy, maintaining the sustainability of rural culture is placed in an increasingly important position [4].

From the perspective of the time node, rural cultural revitalization was put forward during the period when Chinese society was undergoing modern transformation, bringing rural development in China to a new stage. The question raised in this paper is: Since time and space constitute the two dimensions of human practical activities, what does the spatial dimension mean for rural cultural revitalization? Specifically, what kind of cultural space is needed for the sustainable development of rural revitalization? What are the components of such a cultural space? What are the measures through which they can be produced? How do actors work together and are there conflicts? Exploring these questions is of great theoretical and practical significance for realizing the sustainable development of rural culture and the countryside as a whole. Therefore, the researcher went into a typical Chinese village in the northern part of Henan Province and conducted semi-structured interviews with township government staff, village committee members, village cultural organization staff, and villagers' representatives, and coded and analyzed the resulting 30,000-word interview texts using Nvivo12.0 to explore the practice of sustainable rural cultural space production and to explain its structure and mechanism. The study aims to provide theoretical and empirical evidence for rural cultural space production in order to promote the development of the practice of rural cultural revitalization, which in turn supports the sustainable development of rural society.

2. Literature Review

This research focuses on the spatial dimension of rural cultural rejuvenation. Put differently, how do rural cultural spaces support sustainable rural development – known as rural revitalization in China? It should be noted that "rural cultural space" remains a rather broad concept, which can have numerous interpretations or typological divisions, and can also be differentially examined based on geographical variations. This issue has already received attention in relevant studies. To clarify the knowledge gap, after sorting through representative literature, we categorize the research on rural cultural spaces and rural sustainable development into the following aspects.

First, the types of rural cultural spaces. Concepts are crucial to academic research, which is the first step in the study. The concept of "culture" has a broad definition, and different studies take different focuses, which leads to different "rural cultural space." In representative literature, it has the following concepts: (1) Rural public cultural space. Cai X.M. and others used this concept in their research, whose core dimensions are in the physical, power, and symbolic spaces of rural culture [9]. Liu D.L. and Wang K.Q. used this concept in their research as well, but they defined rural public cultural spaces as the places where rural residents participate in cultural activities [10]. Obviously, this concept is more inclined towards the physical attributes of space. (2) Rural cultural memory space. Zhang X.Y. and Li Z.T. used this concept to explore China's rural cultural development, which is related to people's spatial perception and is believed to have a stress-relief effect through landscape design [11]. (3) Rural social cultural spaces. This concept was used in the research of Hu X.L. et al., which is considered the sum of rural social and cultural spaces [12]. (4) Rural tourism spaces. This type of cultural space is related to rural tourism, but tourism activities focus on human rather than natural scenery. Liu X.D. et al. defined it as an experience object for rural tourists in their research [13].

Second, the positive impact of rural cultural spaces on sustainable development. Various rural cultural spaces have been studied by researchers, who have answered the role mechanisms of rural cultural spaces in sustainable development from different angles. Representative literature and views include: (1) Rural cultural spaces enhance residents' happiness through the influence of place attachment. After verifying this view with 1,755 residents, researchers conducted a survey [9]. (2) Rural cultural spaces promote self-development of farmers by mobilizing their active participation in cultural governance activities. Researchers entered this issue from the perspective of cultural governance, explaining the flexible interactive relationship between farmers and the state in rural cultural governance [14]. (3) Promote fair development of rural cultural heritage areas through social space production. Research suggests that through space production, the imbalanced development of cultural heritage areas caused by capital input and power games can be improved [15]. (4) Rural cultural space production can effectively bridge the psychological gap between indigenous residents and new residents. Research shows that the reorganization of rural spaces can effectively bridge the differences between new residents and indigenous residents in terms of status, cultural identity, values, etc. in the process of rapid urbanization [16].

Third, the influencing factors of rural cultural space production. The production of rural cultural space is a complex process that is influenced by various subjective and objective environmental factors. Related literature has pointed out the following two points in close relation to this. (1) Rapid urbanization process. The rapid urbanization process in modern society in developing countries is accompanied by a decline in rural population and culture [17], which is a grim reality that is constantly driving the transformation of rural spatial functions, making the productive agricultural spaces increasingly develop cultural functions and thus giving birth to rural cultural spaces [18]. The large tourism demand brought about by urban development also plays a similar role [19]. (2) Public policy. The positioning of rural development in national institutions and government public policy affects the development of rural culture. A study examined the development of rural cultural spaces in the context of institutional layering, and the different positioning of rural areas in public policy leads to their exclusion from urban and consumption culture spaces [20].

Based on the above literature, this paper believes that there is still room for further exploration in the study of spatial elements of rural cultural revitalization. First, researchers have discussed various types of rural cultural space, such as rural social and cultural space and rural tourism space. But are they independent of each other? Will they be interconnected and influenced by each other? Due to the lack of integrative examination of these different spaces, the relationship between cultural spaces and the overall rural space is ignored, and this is not clear. Second, in the aspect of the impact of rural cultural spaces on rural sustainable development, researchers have examined the mediating effects of rural cultural spaces, but have not highlighted the practical mechanisms of cultural revitalization through rural spatial evolution, i.e., there is still a lack of analysis of the internal structure of rural spaces and their logic in cultural revitalization. Third, in the influencing factors of rural cultural space production, urbanization, population, and public policies have been included in the existing studies, but they are not at the same level. It should be noted that rural areas have various actors, including the government, villagers, and tourists, and what roles do these actors play in the production of rural cultural spaces? In addition, in the intrinsic characteristics of rural cultural spaces, although some studies have attempted to conduct structural examination of this issue, the answers to this question often depend on spatial theoretical models and lack evidence from practical experience.

In summary, we believe that this study contributes to the theoretical discussion of the issue in the following ways: (1) By integrating various cultural spaces identified through coding analysis into a holistic perspective, this study views them as structurally produced rural cultural spaces. Examining rural cultural spaces from the perspective of the whole rural space and evaluating the role of cultural space production in the overall process of rural revitalization is part of the study. (2) This study focuses on the actor factors in the practice of rural cultural space production and systematically analyzes the impacts that multiple subjects in rural society have on this process. (3) Examining the internal structure of rural cultural spaces based on empirical research will provide more empirical information and evidence for the structural analysis based on theoretical models. (4) Unlike existing analytical perspectives, this study includes intellectual elites and civil rights in the scope of investigation and interview, exploring the influence of power, knowledge, rights, and markets on rural culture.

3. Theory, Materials and Methods

3.1. Theory

In recent years, spatial theory has been increasingly emphasized and applied in various fields of research by Chinese scholars, and the spatial turn in philosophy and social sciences after the mid-twentieth century has contributed to a renewed understanding of social, political, and historical issues, including, of course, culture [15]. Lefebvre's trinity theory of space reveals the political, practical, and living nature of space, which makes people's understanding of "space" go beyond the geographical and physical connotations of "place" and "territory" [16]. Although Lefebvre does not directly explain the term "cultural space", he argues that space can be marked in the abstract using discourse and symbols when discussing spatial production. Space then acquires a symbolic value, and this expression implies the cultural attributes of space, thus providing a theoretical possibility to explain the development and evolution of cultural space from the perspective of spatial production. Since then, the cultural and emotional properties of space have been further clarified in Turgot's research [17].

In the field of rural cultural studies, along the lines of Lefebvre's reflections, rural cultural spaces are usually distinguished as spaces of power, spaces of perception and spaces of life. This distinction is in line with Lefebvre's theory of spatial production, but the structured theoretical model is not necessarily suitable for all spatial studies. After all, the sustainable development of rural culture in different regions always faces different problems due to different policies, histories and socio-economic backgrounds. Especially in China, the different degree of urban-rural disparity, differences in local policies and heterogeneity from customary traditions make the development of rural culture in China more complicated. Empirical and practical evidence must be taken into account in the scope of the study. Therefore, the application of spatial theory in this study is more in the way of thinking and the logic of analysis, and the practice situation of the case sites will be largely included in the structured analysis of rural cultural space.

From a spatial per spective, we can define rural cultural space as a public space defined by the cultural attributes of the rural space as a whole, which includes both the physical carriers that carry the cultural activities of the residents, as well as the non-material contents of traditional culture, folk customs, ideology and morality. Rural cultural space is not a pre-existing, static, but a relational, productive existence. It can be said that this space is not only dependent on the rural space in the physical or geographical sense, but also will acquire a relatively independent attribute along with the implementation of the strategy of cultural revitalization and artificial construction. This property points to the shaping of space by people as individuals or groups and is also constrained by various structural elements, such as political structures, when people produce the cultural properties of space [18]. We believe that this analysis remains within the scope of spatial theory and is in line with the line of research indicated by Lefebvre. Based on this, we define the rural culture space production as a process in which diverse rural on-site actors manage, reshape, and update rural cultural elements such as traditional customs, moral and ethical beliefs, etc., through their practical activities to highlight the cultural identity of rural spaces.

We believe that rural cultural revitalization is the process of reshaping the spatial structure of rural culture and rebuilding the spatial value of rural culture in the modern transformation of traditional villages, so that the cultural attributes of rural space can be manifested. This research needs the guidance of spatial theory for the following considerations. First, as the core object of the spatial theory system, spatial production theory helps to recognize and analyze the internal structure of rural cultural revitalization, i.e., what organic parts the cultural space of rural revitalization consists of. This will provide principled and goal-oriented guidance for our coding analysis. Second, spatial theory considers scale reconfiguration as the core mechanism to see through the process of spatial production and to realize the goal of spatial justice, which is mainly the process in which elements such as power relations, power structures, and resource allocations of spatial actors are changed so as to form new spatial scales [19]. This provides a perspective that can be relied upon to analyze the power relations of rural actors. Rural cultural revitalization is a systematic project, and its spatial practice involves multiple subjects such as governmental public power, citizens' private power, technological power, capital power, etc., and the power scale becomes an important perspective for analyzing rural cultural revitalization. Combining spatial political theory to explore rural cultural revitalization, we should analyze the cooperation mechanism and tension logic of rural power subjects in the field, and propose the practical direction of power adjustment on this basis. In other words, in the production of cultural space for sustainable development in the countryside, the internal structure of cultural space and its subjective logic affect the process of cultural revitalization in the countryside. This is the inspiration that spatial theory brings to this study, and it also shows the applicability of this theory in the study.

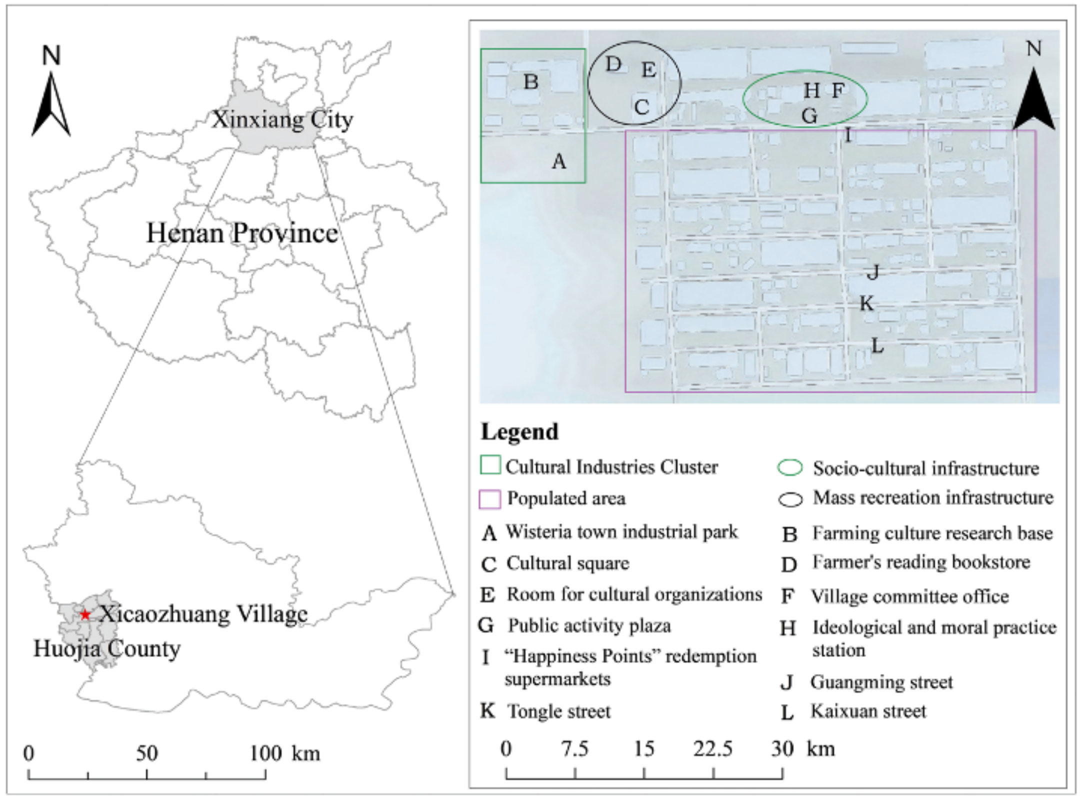

Fig. 1. Geographic Location of Xicaozhuang Village and Distribution of Cultural Facilities in Henan Province

3.2. Materials

3.2.1. Case Site Profiles

This study conducted research and interview activities in Xicaozhuang Village. The main reason for conducting the research here is due to the consideration of such recursive relationships: (1) Rural cultural development is a worldwide topic, and as the world's largest developing country and a large agricultural population, China's practice cases can provide empirical references for this topic. (2) Some typical traditional villages, those villages that have been greatly influenced by history and culture, have more prominent significance in the transformation and development of culture in modernity. In China, a large number of these villages are clustered in the Central Plains, especially in Henan Province, which carries the thick historical and cultural memories of China. (3) Xicaozhuang village, located in the north of Henan Province, has the local characteristic of "alliance culture", which is related to the story of King Wu's conquest of King Zhou in Chinese history. We believe that this village's emphasis on distinctive culture and its attempts at industrialization are worthy of reference. To summarize, in a situation where traditional village culture is facing difficulties in transformation and weakening of subjectivity, the development strategy of cultural revitalization in Xicaozhuang Village provides a typical and good case for this study.

Xicaozhuang Village is located in Shizhuang Town, Huojia County, Xinxiang City, Henan Province, with a total of 212 households and 912 people in the village, which is divided int o four villagers' groups. The village is located in the southwestern part of Huojia County, 30 kilometers away from Xinxiang city and 5 kilometers away from Huojia County, adjacent to Xinjiao Highway in the north, and the Tsukafeng Line passes through the western part of the village.

In the early days of China's reform and opening up, Xicaozhuang Village was one of the first villages in Shizhuang Town to build a new countryside, with unified planning carried out as early as 1983, and housing remodeling carried out in the mid-80's. 2009 the end of the year, the village through the village collective fund-raising and villagers donations to build the elderly activity center, and then successively built the cultural square, farmhouse, civilization, cultural center and cultural center. The village has established a cultural cooperative to manage the cultural facilities in the village, and since 2014, the village has set up a drum team, dance team, Yangko troupe and other cultural organizations, and the development of the village's cultural undertakings has become increasingly mature. 2021, Xicaozhuang village has become a pilot village in the town of Shizhuang for the promotion of rural revitalization and development, and the government has invited experts from the think tank to stay in the village. And through the “village collective capital + villagers share + enterprise investment” to set up a farming culture study base, forest restaurant and other collective industries, integrating the resources of various cultural organizations in the village to help the village achieve the transformation and development. At present, the study project has been fully completed and put into use, receiving students from all over the world and study teams no less than 3 times a week, the village cultural organizations to carry out various activities on a regular basis, forming a village cultural revitalization pattern under the leadership of the village two committees, with farming culture study base as the industrial backing, based on the cultural organizations in the village.

3.2.2. Data Material Collection

In order to examine the behaviors of different subjects and their roles in the spatial production of rural cultural revitalization, the objects included in this study include four types of subjects involved in the cultural revitalization of Xicaozhuang Village: the government and village committees, think tank experts, cultural organizations, and villagers. Therefore, this study takes the staff of the government and village committees, the members of the think tank expert group, the members of the village cultural organization, and the villagers as the interviewees, and goes to Xicaozhuang Village for field research in the early stage from July 5 to 15, 2023, during which a total of 12 people were interviewed, and then later on contacts the interviewees and carries out the tracking return visit through telephone and WeChat. In the field research stage, potential interviewees were contacted through recommendations from acquaintances, and then the sample size was gradually expanded through the “snowballing” method, and the interviews were audio-recorded after explaining the purpose of the research and obtaining the consent of the interviewees. At the end of the field research, more than 30,000 words of text were obtained through transcription of the audio files. The sample of field interviews is shown in Table 1, where ZC represents government and village committee staff, ZK represents village-based think tank experts, WZ represents members of village cultural organizations, and CM represents villagers.

3.3. Methods

Grounded theory is a mature and influential qualitative research method, which has been more and more popular since the 1960s. The value of this research method lies in producing richer conceptualization of data coding and possible interpretation of data observation [20]. It has significant advantages in collecting data, defining core concepts, exploring the relationship between social phenomena, constructing theories and so on. As a concept and theory generation method, grounded theory can deal with different forms of data, usually qualitative interviews [21], also including focus groups [22], participatory observation [23] and quantitative data [24]. Classical grounded theory usually defines the research procedure as (1) open coding, (2) selective coding, and (3) theoretical coding [25]. The first two procedures point to the substantive coding and analysis of the data, while the theoretical coding is the construction and interpretation of the model.

The applicability of the methodology lies in terms of the purpose of this study and the characteristics of the data. First, this article undertakes an exploratory study on rural cultural revitalization

Table 1. Basic information of interview sample.

Basic information of interview sample	Gender-based	Age	Social Status
ZC1	Woman	34	Government staff
ZC2	Man	48	Members of village committees
ZC3	Woman	55	Members of village committees
ZK1	Man	39	Think tank expert
ZK2	Woman	35	Think tank expert
WZ1	Woman	44	Membership in cultural organizations
WZ2	Man	44	Membership in cultural organizations
WZ3	Woman	47	Membership in cultural organizations
CM1	Man	69	Villager
CM2	Woman	20	Villager
CM3	Woman	46	Villager
CM4	Man	37	Villager

from the spatial perspective. Therefore, it is suitable to use grounded theory for qualitative analysis. Second, as a qualitative study, the data collected in this paper are interview texts. As mentioned earlier, g This type of data is within the analytical purview of grounded theory. In this study, qualitative textual data were collected through semi-structured interviews. Using Nvivo 12.0 as a tool to collate and analyze the interview data, according to the results of the analysis, the production structure model of cultural space for sustainable development is constructed.

It should be noted that although grounded theory has gained increasing application, the possible limitations and subjectivity in the coding process are well recognized. To avoid deviations in the coding analysis, the following efforts were made: (1) At the coding stage, each member of the team conducted independent conceptualization and coding to prevent subjective randomness in the coding process. Any differences and disputes that emerged during this process were reviewed and discussed collaboratively within the team, and a shared final coding list was formulated after identifying similar-

Table 2. Examples of open coding analysis

Texts of interview materials	**Initial conceptualization**	**Generalization**
Because the rural areas, the most important thing is the development of agriculture, nowadays technology is getting more and more developed, but the most fundamental thing in the countryside is still farming, which is also a kind of culture in itself. (ZC2)	a1 The nature of rural areas	A1 Agrarian culture
It's true that what we farmers know best is farming, but it's really a culture that not only rural areas need to know about, but cities can learn about it as well. (CM1)	a2 Agricultural culture	
Our Huojia County is the town of alliance, according to legend, King Wu of Zhou and the lords of the alliance here in the mountain after the oath of the Makino war, after the end of the war in order to pay tribute to the memory of the dead warriors, the king of Wu in the graves to add soil, the formation of the seventy-two mounds of the Huojia, the largest one in the village of Caozhuang in the West. (ZC1)	a3 Local history and culture	A2 Allied culture
We actually had seven villages to choose from at the time to do this rural revitalization planning, and we finally chose this village also because it has this unique history ......(ZK2)	a4 Cultural uniqueness	
Our village's own children, from an early age, we must let the village children know this history and culture of their own ...... (CM4)	a5 Kindergarten education	A3 Responsibility awakens
Our village has its own kind of character, and it's everyone's kind of responsibility to develop it well. (ZK1)	a6 Responsibility for rural development	
Every year we have village representatives selecting the most beautiful family, the most beautiful in-laws, and so on, which are announced on the bulletin board of the village committee. (ZC3)	a13 Comparison of advanced individuals	A6 Model breeding
The judging was all very positive, it's a recognition and an honor for everyone ......(CM3)	a14 Participation of villagers	
Pension policy, social security policy, funeral reform and so on these national policies are often popularized to everyone, so that you also master this knowledge. (ZC2)	a27 Policy briefing	A13 Popularization of policy and theory
I think it is necessary to let the people know about some new theoretical knowledge of the Communist Party of China, and it is good to organize a little lecture or something for people to listen to. (CM2)	a28 Theoretical popularization	
Our research base has five types of handicraft programs including tea art and cloth art, all of which are staffed by full-time personnel who can guide students who come here for a comprehensive experience. (ZK1)	a63 Handicraft experience	A30 Craft project experience
Research base we also understand that the projects there are combined with the development of farming civilization, but also consider the culture of our village and the selection of personnel ......(CM4)	a64 Project selection	
……	(Total 78 initial conceptualization)	(Total 36 generalization)

ities and differences. (2) During the coding process, an open attitude was maintained towards new and unexpected concepts, and they were reviewed in accordance with the research objectives. (3) Stringent attention was paid to the accuracy and consistency of coding to accurately interpret and present the research results in the subsequent analysis. (4) There are four types of subjects included in this study. In the theoretical saturation test stage, four Xicaozhuang village related characters (one for each subject respectively) were selected again through theoretical sampling to carry out semi-structured interviews, and the same process of organizing and coding was carried out on the obtained interview data, and it was found that no new factors appeared in the obtained main categories, which indicated that the categories in the spatial production model obtained from the study had been saturated.

4. Data Coding and Analysis

4.1. Open Coding

Open coding refers to the continuous comparison and analysis of the qualitative information obtained in the preliminary stage of the study, before determining the coding of the central categories and their characteristics, breaking up the qualitative information obtained and carrying out a preliminary conceptualization and categorization, with the aim of discovering categories of concepts from the raw information, assigning corresponding concepts to each of the categories, and on the basis of which associated concepts are grouped together to form a category. In this study, Nvivo 12.0 is used as a tool to analyze the interview data word by word, line by line, and paragraph by paragraph using the free coding function, and 78 initial free nodes are formed. Afterwards, repeated comparisons are made between the nodes and between the nodes and the text of the interviews, and the initial concepts with a reference point of less than 2 are excluded, and concepts that are related to each other with similar meanings are integrated, so that 36 corresponding categories are obtained. The coding examples are shown in Table 2.

4.2. Axial Coding

Axial coding refers to the discovery or establishment of connections between the many conceptual categories obtained from open coding in order to unfold the logical connections originally scattered among the concepts, which requires the researcher to cluster the concepts obtained from open coding based on the similarities and dissimilarities between the concepts through repeated comparisons to form the main categories and subcategories. In this study, through gradual refinement and based on the links between the 36 conceptual categories obtained from the open coding, a total of four main categories were identified that can unify the above concepts, namely, Local Culture Space, Socio-cultural Space, Mass Recreational Space and Cultural Industries Space(see Table 3), and the above four types of space together constitute the multidimensional spatial structure of the rural culture.

4.3. Selective Coding

Selective coding refers to the process of further analyzing and summarizing and integrating the main categories formed in the early stage, which is the process of forming a “story line” in grounded theory. Based on the concepts and categories developed by open coding and axial coding, this study explores the core category of “spatial production of rural cultural remodeling” through in-depth analysis of primary interview data and further develops the “story line” of this research.

As a representative place of farming culture and allied culture, the two local cultures have always been potential in the native rural space of Xicaozhuang Village, without effective integration and development. Due to the improvement of economic level and the development of spiritual life needs, the village has built cultural infrastructures such as senior citizen's activity room, village library, etc., and gradually set up cultural organizations such as drum team and dance team under the leadership of the government and the village committee, which laid the groundwork for the development of the socio-cultural space and mass recreational space in the village. Along with the interaction of the above cultural venues and organizations in the village's native space, these two types of cultural space can be produced and reproduced.

As a result of cooperation with the local government, a group of think-tank experts focusing on rural governance and development have moved into the village, with the goal of “empowering the revitalization of villages and the development of the village”. ...... in this village to create a harmonious countryside where 'each one is beautiful, and the beauty is shared'.” (ZK2) This idea fits with the goal of village revitalization. After moving into the village, they found that Xicaozhuang village “has its own location advantage, close to the county town, and also has its own characteristics of farming culture and alliance culture ......” (ZK2) began to work with the village two committees to integrate the village's cultural resources, create farming culture and allied cultural characteristics, carry out environmental renovation, build a farming culture study base on the basis of the old site of the abandoned elementary school, and build the “Furuwang Brewery” on the basis of the abandoned brewery, to comprehensively display the farming culture on the basis of wine culture, tea art, cloth art, and gradually promote the integration of culture and tourism, and establish the “forest restaurant”, children's playground and so on.

While integrating local culture and developing cultural industries, the cultural space of the countryside can be extended, and in the process of multi-party cooperation and interaction, the space of local culture and the space of cultural industries are formed, and the production and reproduction of the four types of space together constitute the spatial production mechanism for the revitalization of rural culture.

Table 3. Analysis of axial coding.

Corresponding category	Main category	Secondary category
Local Culture Space	Integration of cultural resources	A1 Agrarian culture
		A2 Allied culture
	Cultural inheritance	A3 Responsibility awakens
		A4 Innovative forms of education
Socio-cultural Space	Model leadership effect	A5 The CPC members' driving force
		A6 Model breeding
		A7 Village-Enterprise cooperation
		A8 Material incentive
	Building a civilized village culture	A9 Policy guidance and coordination by village committees
		A10 Strengthening village autonomy
		A11 Social organization communication
	Cultivation of new farmers	A12 Exchange platform building
		A13 Popularization of policy and theory
		A14 Production technology training
		A15 Self-directed learning for villagers
	Centripetal cohesion	A16 Sense of ownership
		A17 Harmonious rural construction
		A18 Local flavor of life
Mass Recreational Space	Construction of cultural facilities	A19 Government supports
		A20 Participation of village sages
		A21 Contributions from villagers
		A22 Personalized management
	Cultural organization formation and development	A23 Villagers' needs
		A24 Funding and operations
		A25 Teaching of artistic skills
	Public cultural activities	A26 Independently conduct
		A27 Creative activities
Cultural Industries Space	Industrialization of culture	A28 Research and study system construction
		A29 Digital technology empowerment
		A30 Craft project experience
	Cultural symbolization	A31 Architectural painting
		A32 Song writing
		A33 Cultural branding
	Cultural and tourism integration	A34 Construction of supporting facilities
		A35 Tourism planning
		A36 Environmental remediation and protection

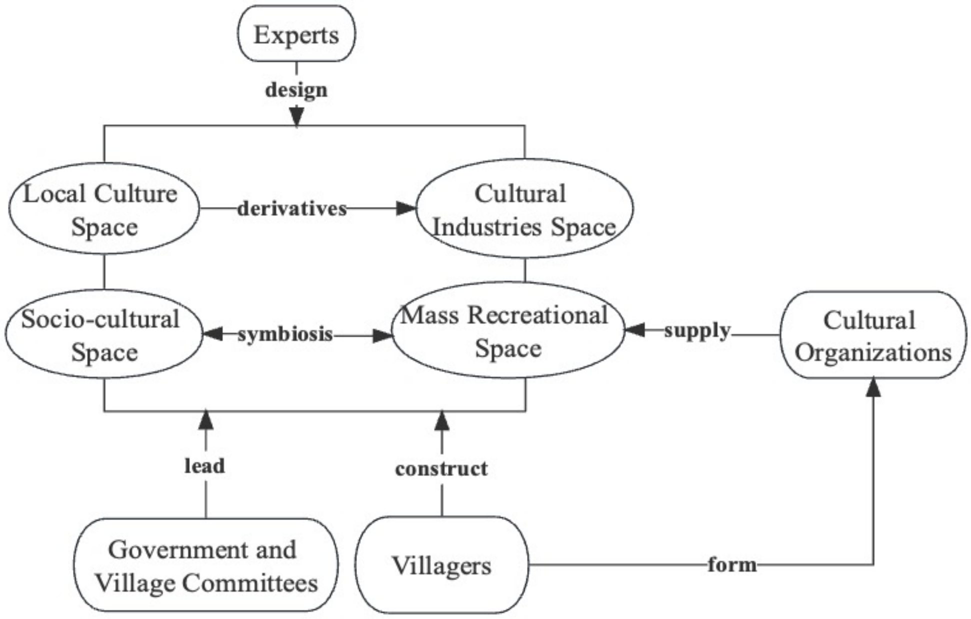

Fig. 2. a

5. Theory Construction and Interpretation: How Space Is Produced?

The results of the coding show some structural characteristics of rural cultural space on the one hand, and provide a basis for analyzing the influence mechanism of actors on the other. The production of cultural space oriented to the sustainable development of rural revitalization is not dominated by a single subject, but is the product of the forces exerted on rural space by different subjects based on their own needs and interests, and its core mechanism is the collaboration of multiple subjects, which stimulates the cultural vitality of the countryside. Studies have explored the interactions of power, value and capital in the production of cultural space in rural China [26, 27]. On this basis, this article incorporates experts as intellectual elites and cultural organizations as products of citizens' cultural rights into the network of actors in the production of rural cultural space.

From the 12 main categories shown by the axial coding, these activities are entirely carried out by different actors. Combining the 36 secondary category and an in-depth analysis of the interview materials, we can observe that: in the process of spatial production, the intervention and interaction of multiple sub-subjects lead to the construction of new vernacular cultural space, social cultural space, mass recreational space and cultural industry space on the fragmented rural vernacular cultural space. Vernacular cultural space, social cultural space and mass recreational space are endogenous spaces under the influence of policies and people's demands, and the subjective role of the villagers and their practice of social interaction have had a fundamental impact on the production and reconstruction of spatial scales. The space of cultural industry is a composite space generated under the joint action of the internal subjects of the countryside and the external thrust of the market. It not only contains the cultural space embedded in the countryside, but also produces a series of derivative spaces along with the development of the industry and the further promotion of the integration of culture and tourism.

Based on the coding analysis and theoretical analysis, this study attempts to construct a sustainable cultural spatial production model for rural revitalization (Fig. 1). This includes the structural characteristics and actor logic of rural cultural spatial production.

Based on Fig. 2, the roles of different actors in rural society in the production of space and their relationships can be summarized as follows:

a. In the production of local cultural space, because of the complexity of the expertise and programming required to organize the non-systematic cultural resources that exist in villages, the main actors in this process are the government and village committees. They take the initiative in exploring and integrating the cultural resources of the village and guiding the villagers to participate in the production of space, etc. With the think tank experts hired by the government and stationed in the village, the experts

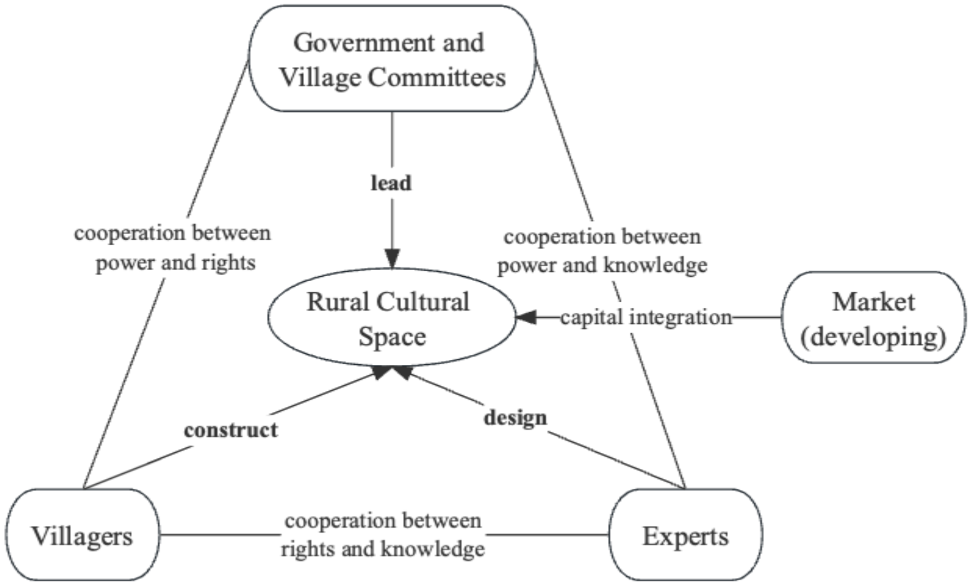

Fig. 2. b

Fig. 2. Sustainable Cultural Spatial Production Model for Rural Revitalization: (a) Roles of Rural Actors in Shaping the Four-Dimensional Structure of Cultural Space; (b) Interplay of Power, Rights, Knowledge, and Capital in Cultural Space Production, Including Villager-Established Cultural Organizations and Emerging Market Dynamics

have the right to speak on the overall planning of the development of the village, including the overall design of the production of local cultural space. In the process of government guidance and expert planning, the production of local cultural space can form a synergy only after the villagers' subjectivity has been brought into play by arousing their awareness and recognition of local cultural characteristics.

b. In the production of socio-cultural space, villagers occupy a central position in the production of space, and the main function of the government is to guide the direction of social and cultural development. The ideological and moral concepts of the villagers are becoming more and more perfect under the guidance of the government, and they are constantly exchanged and collided in the daily interaction practice, and this interaction is also the process of awakening the consciousness of the main body of space production. Along with the advancement of the process of rural civilization construction, the social and cultural construction of villagers' self-governing organizations is becoming more and more perfect, and the majority of villagers have changed from “followers” of spatial production to “pro-experiencers”, constantly updating the rural social and cultural space, so as to make it develop into a promotion of rural spatial carrier of ideological and moral revitalization.

c. In the production of mass recreational space, the role of the villagers' subjectivity becomes the core of spatial production. This spatial production requires respect for and maintenance of the basic rights of farmers to independent choice, standardization, participation in the process and access to benefits, with the ultimate goal of farmers' happiness and satisfaction [28]. The public cultural services carried out by various cultural organizations formed by villagers as the main body of action provide the content of spatial production, which in turn renews the cultural needs of villagers, and the interaction between the two dominates the production and reproduction of mass recreational space. At the same time, the government and village committees also cultivate this space through relevant policy support and publicity and promotion actions.

d. In the production of cultural industry space, all parties are involved in the interaction and production of space: the government provides policy support, village committees are responsible for specific coordination, think-tank experts undertake planning and design, and all kinds of cultural organizations in the village rely on the construction of the industry for further devel-

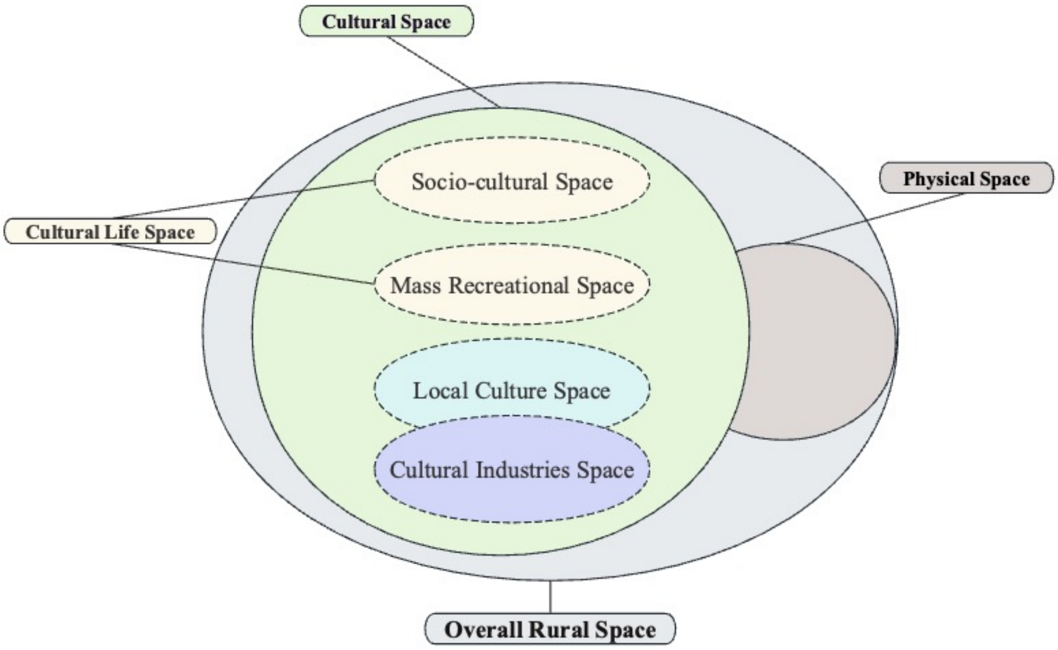

Fig. 3. The spatial system for rural cultural revitalization

opment, but from the perspective of industrial development and industry improvement, this space is always still centered around the villagers. The cultural industry relying on the local characteristics of culture has been set up from the beginning as a way of villagers' shareholding and joint management by the village collective, and only when the villagers' subjectivity can be brought into full play, the subsequent housing renovation, land use planning, capital turnover, construction and so on can be put into practice. Along with the establishment of cultural industries and the future development of cultural tourism integration, this space will welcome a large number of tourists, researchers and other foreign subjects, and their interaction with the subjects within the space will become an important formation mechanism of the cultural industry space in the future.

e. In the spatial production practice of cultural revitalization in Xicaozhuang Village, all kinds of official media reports have continued to explain the logic of its spatial production, and these explanations of the official discourse system have also provided a reference for examining the results of this study in the process of grounded theory. In its report on the practice of cultural revitalization in Xicaozhuang Village, the Bureau of Rural Revitalization of Xinxiang City points out that the practice in Xicaozhuang Village "creates a civilized, festive, and harmonious atmosphere in the countryside, and guides the masses to respect virtue and goodness, and to see the virtuous and the wise, so that the villagers' love for their hometowns and enthusiasm for their countryside are born from within and are continuously transformed into the positive energy of revitalization of the countryside". In the official media's discourse construction of rural revitalization in Xicaozhuang Village, "homemade golden key" is always the core theme, fully reflecting the core role of villagers' subjectivity in the spatial production of rural cultural revitalization, and at the same time, revealing the logical underpinning that the promotion of rural revitalization must rely on the majority of the people; in addition to the following "Resource Integration, Highlighting Characteristics", 'Civilization Construction', 'Organization of Public Cultural Activities', "Study Base Project " and other aspects of the report from the side of the local cultural space, social and cultural space, mass recreational space and cultural industry space co-production in the rural cultural revitalization of the synergy role.

To sum up, the spatial production of rural cultural revitalization is not only embodied in the production and reproduction of material space and its practices, but also implies the reconstruction of social relations that accompanies it, with different types of space being constructed by different relational subjects. The production of vernacular cultural space is based on the ability to integrate and creatively transform vernacular cultural resources;

the key lies in the ability of villagers to integrate into the new space guided and planned by the Government and professionals. Social and cultural space and mass leisure space have a symbiotic relationship in the village culture as a whole, which makes the development of social culture associated with the cultural needs of villagers, and the spatial production of both is dominated by villagers and the various cultural organizations they form. The spatial production of these two is led by villagers and their various cultural organizations. The spatial production of cultural industry is based on the construction of local culture to create cultural characteristics, and the professional planning and villagers' participation in this process play a crucial role. With the advancement of the integration of cultural industry and culture and tourism, the gradual improvement of the local economy and the process of spatial production will have a renewing effect on the social and cultural space and the mass recreation and entertainment. On the other hand, will influence the spatial production of rural cultural revitalization by guiding the healthy and orderly development of local culture and cultural industries related to it, and cultivating social culture and mass cultural organizations.

In order to show the spatial changes more intuitively brought about by the production of rural cultural spaces, we drew a network diagram of the relationships between different spaces (Fig. 3).

6. Conclusive Remarks

In existing research on rural revitalization, scholars have examined a great deal of spatial issues in the “physical-geographical” sense, including the spatial system of rural settlements [29], environmental graphics in rural tourism space [30], and the geographical distribution of the livability of rural space [31]. In fact, as long as there are human social activities, any space will have structural, social and even political characteristics. Physical and geographical spatial analyses certainly provide us with intellectual insights into rural revitalization and rural development, but they are also far from sufficient. Under the idea of spatial production theory, this article, based on survey interviews in villages in northern Henan, China, uses grounded theory to explore the sustainable cultural spatial structure oriented to rural revitalization and the cooperative mechanism of actors behind it. The results show that the spatial production of cultural revitalization is a process in which multiple actors and multidimensional spaces are jointly promoted, and local cultural space, social and cultural space, mass recreational space, and cultural industry space are produced on the basis of local characteristic culture and old resources. The production process of multi-dimensional spatial structure stimulates the subjectivity of rural cultural revitalization and the characteristics of rural cultural construction, and supplies cultural resources and spatial carriers for the long-term sustainable development of rural culture. Cultural revitalization is an important measure to empower rural revitalization. The revitalization of distinctive culture, the revitalization of ideology and morality, the revitalization of public cultural life and the revitalization of the cultural industry constitute the "four beams" of rural cultural revitalization, which are put into spatial practice through the construction of the distinctive cultural space, the social and cultural space, the mass recreational space and the cultural industry space, respectively.

Till now, we contend that the conclusions and their interpretations obtained through the coding analysis of grounded theory as mentioned above are in line with the actual circumstances. This is primarily based on the following aspects. Firstly, coding analysis constitutes a crucial link in grounded theory, and we have adopted certain measures to avoid subjectivity in this process, as detailed in Section 2.3. Secondly, grounded theory relies on empirical data, which originate from social practices. We compared and restored the research results with the practical situation of Xicaozhuang Village: through communication with the members of the village committee and think tank experts, we presented this research and its conclusions to them, and they regarded it as realistic. Finally, this paper examines the roles of power, rights, knowledge, and capital in rural cultural revitalization. The actors in these four aspects are widely present in various political practices in China. We believe that the conclusions are in accordance with the practical situation of rural cultural revitalization in China.

This study provides a theoretical and empirical basis for understanding the network of actors and their cooperative relationships in rural development in the Chinese context: (1) The government and village committees have integrated the fragmented cultural resources in the countryside through the use of public power for policy guidance, cultural governance, and the construction of official discourse based on the demands of “order and development”, constructing a power structure in the rural cultural space. It has constructed the logic of power in the rural cultural space. (2) As intellectual elites in the rural space, think-tank experts, based on their technical expertise and personalized management planning, supply the overall idea of rural cultural development through resource integration and technological transformation, and construct the logic of knowledge (technology) in the rural cultural space. (3) Based on the goal of “livability and happiness” given to the rural space by the local villagers and the cultural organizations formed by them, the villagers play the main role of producing and reproducing the content of the rural cultural space through independent participation and active construction, thus constructing the logic of rights in the rural cultural space. (4) Along with the development of cultural and tourism integration and cultural industry in the future, the rural space will give rise to a kind of consumption and circulation space such as tourism space regulated by the market mechanism, and then the capital factor will also participate in the production of the rural space. This conclusion can complement the neglect of rural intellectual elites, citizens and their rights organizations in existing studies [26, 27,32].

The findings of this study may have practical implications for policy formulation, practice paths, and action strategies for sustainable cultural development in other rural areas of China. In empirical studies of cultural sustainability in rural China, southern regions with higher levels of economic development [33] and villages with well-established program support [34] are usually taken as the object of study. As a matter of fact, more Chinese villages are in the central and western regions without special support from the national, provincial or even municipal level. The level of economic development and the disadvantage of resource allocation make the cultural development of these villages face a lot of dilemmas, and the introduction of market and capital requires fine planning, and the discovery of economic growth points. Therefore, as one of the villages, based on the experience of villages in northern Henan, the four-dimensional rural cultural space found in this study provides a largely generalizable structural path for cultural space production oriented to rural revitalization: (1) The historical and cultural characteristics of villages on the ground provide the soil for the production of local cultural space and its transformation into a cultural industry, and at the same time, it is the fundamental dependence on which to get out of the dilemma of homogeneous development of rural cultural revitalization. (2) The production of social cultural space and mass recreational space has become an effective carrier for the villagers' subjectivity and public cultural life. (3) The creation of the four-in-one composite spatial form is more capable of providing cultural resources for the sustainable development of the countryside. (4) In addition to the actors' cooperation, this study analyzes the possible conflicts between them. This power asymmetry should be noted and addressed in more rural cultural revitalization practices.

It must be noted that the production of cultural space in the countryside is a complex and long practical process, and the research in this article is only a part of this major topic. In terms of the structure of cultural space production and its actor mechanisms, this study will continue. Future research includes, but is not limited to, the following questions: With the improvement and development of the cultural industry, will rural cultural spaces become increasingly commercialized due to market mechanisms after the entry of market players? How do the various cultural organizations in the countryside adapt to the market access? What is the specific interaction mechanism between rural spatial production and rural governance? Of course, conducting comparative research on different types of villages will also be an important academic direction, whether these types are classified from the perspective of economic level, regional characteristics, or demographic structure or cultural patterns.

Author Contributions

Conceptualization, H.W. and C.L.; methodology, K.A.; software, H.W.; validation, H.W., C.L. and K.A.; formal analysis, H.W.; investigation, H.W. and C.L.; resources, K.A.; data curation, H.W.; writing—original draft preparation, H.W., C.L. and K.A.; visualization, H.W. and C.L.; supervision, C.L. and K.A.; project administration, H.W. and C.L.; funding acquisition, K.A. All authors have read and agreed to the published version of the manuscript.

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References

1. Harbiankova, A.; Gertsberg, L. Information Model for Sustainable Rural Development. *Energies*.**2022**,15,4009. DOI10.3390/en15114009.
2. Liu, Y.; Qiao, J.J.; Xiao, J .; Han, D .; Pan, T. Evaluation of the Effectiveness of Rural Revitalization and an Improvement Path: A Typical Old Revolutionary Cultural Area as an Example. *International Journal of Environmental Research and Pubic Health*.**2022**,19,13494. DOI10.3390/ijerph192013494
3. Cui, Y.Y.; Wang, Y.J.; Jiang, J.S. Sustainable Development of China's Intangible Cultural Heritage in Rural Revitalization based on Experience Perspective. *Problemy Ekorozwoju*.**2024**,19,265-271. DOI:10.35784/preko.5809
4. Liu, X.D.; Zhang, J.C.; Zhou, Z.C.; Feng, Z.Y. Investigating the Impact of Environmental Graphics on Local Culture in Sustainable Rural Cultural Tourism Spaces. *Sustainability*.**2023**,15,10207. DOI:10.3390/su151310207
5. Cai, X. M.; He, J.; Liu, M.X.; Morrision, A.M.; Wu, Y.Q. Building rural public cultural spaces for enhanced well-being: evidence from China. *Local Environment*. **2024**,19,540-564. DOI10.1080/13549839.2024.2306593
6. Liu, D.L.; Wang, K.Q. Research on the Siting of Rural Public Cultural Space Based on the Path-Clustering Algorithm: A Case Study of Yumin Township, Yushu City, Jilin Province, China.*Sustainability*.**2023**,15,1999. DOI10.3390/su15031999
7. Chang, X.Y.; Li, Z.T. Tourists' Perceived Restoration of Chinese Rural Cultural Memory Space. *Sustainability.***2022**,14,14825. DOI10.3390/su142214825
8. Hu, X.L.; Li, H.; Zhang, X.L.; Chen, X.H.; Yuan, Y. Multi-dimensionality and the totality of rural spatial restructuring from the perspective of the rural space system: A case study of traditional villages in the ancient Huizhou region, China. *Habitat International.***2019**,94,102062. DOI10.1016/j.habitatint.2019.102062
9. Liu, X.D.; Zhang, J.C.; Zhou, Z.C.; Feng, Z.Y. Investigating the Impact of Environmental Graphics on Local Culture in Sustainable Rural Cultural Tourism Spaces.*Sustainability*.**2023**,15,10207. DOI10.3390/su151310207
10. Chen, N.N. Governing rural culture: Agency, space and the re-production of ancestral temples in contemporary China. *Journal of Rural Studies*. **2016**,47,141-152. DOI10.1016/j.jrurstud.2016.07.029
11. Wu, C.; Yang, M.L.; Zhang, H.; Yu, Y.F. Spatial Structure and Evolution of Territorial Function of Rural Areas at Cultural Heritage Sites from the Perspective of Social Space.*Land.***2023**,12,1067. DOI10.3390/land12051067
12. Zheng, N.N.; Wang, S.C.; Wang, H.Y.; Ye, S.Q. Rural settlement of urban dwellers in China: community integration and spatial restructuring. *Humanities & Social Sciences Communications*.**2024**,11,188. DOI:10.1057/s41599-024-02680-8
13. Ye, C.; Ma, X.Y.; Gao, Y.; Johnson, L. The lost countryside: Spatial production of rural culture in Tangwan village in Shanghai. *Habitat International*.**2020**,98,102137. DOI10.1016/j.habitatint.2020.102137
14. Li, S.A.; Congmou, Z.; Li, Y.J.; Dong, B.Y.; Tan, K.; Deng, X.D. Agricultural space function transitions in rapidly urbanizing areas and their impacts on habitat quality: An urban-Rural gradient study. *Environmental Impact Assessment Review*. **2023**,99,107017. DOI10.1016/j.eiar.2022.107019
15. Barney W. Santa A. The Spatial Turn: Interdisciplinary Perspectives; Routledge Press: London, UK,2008; pp.1-3.
16. Henri L. *The Production of Space*; Blackwell Press: New Jersey, USA,1991; p.33.
17. Durkheim E. *The Basic Form of Religious Life;* Shanghai People's Publishing Press: Shanghai, China,1999; pp. 13- 22.
18. Karen N. Peter K. *Space, Place, and Environment*; Springer Press: Berlin, Germany,2016; p.3
19. Song,D.L.; Cong B.D. Spatial Politics:Spatial Politics Based on the Analytical Framework of Spatial Turn.*Dongyueluncong*.**2021**,42(07):174-182+192(in China).DOI:10.15981/j.cnki.dongyueluncong.2021.07.018.
20. Birks, M.; Hoare, K.; Mills, J. Grounded Theory: The FAQs. *International Journal of Qualitative Methods*.**2019**,18,1609406919882535. DOI:10.1177/1609406919882535
21. Timonen, V.; Foley, G.; Conlon, C. Challenges When Using Grounded Theory: A Pragmatic Introduction to Doing GT Research. *International Journal of Qualitative Methods*.**2018**,17, 1609406918758086. DOI:10.1177/1609406918758086.
22. Hennick M. M. Focus group discussions. Understanding qualitative research; Oxford University Press: Oxford, UK,2014.
23. Laitinen H.; Kaunonen M.; Astedt-Kurki P. Methodological tools for the collection and analysis of participant observation data using grounded theory. *Nurse Researcher*.**2014**,22, 10–15. DOI:10.7748/nr.22.2.10.e1284
24. Glaser B.; Strauss A. The discovery of grounded theory: Strategies for qualitative research,5th.; Aldine Transaction: London, UK,2010.
25. Holton J. A.; Walsh I. Classic grounded theory: Applications with qualitative and quantitative data; Sage: CA,USA,2016.
26. Dai, M.L.; Fan, D.X.F.; Wang, R.; Ou, Y.H.; Ma, X.L. Does rural tourism revitalize the countryside? An exploration of the spatial reconstruction through the lens of cultural connotations of rurality. *Journal of Destination Marketing &*

Management.**2023**,29,100801. DOI: 10.1016/j.jdmm.2023.100801

27. Cai, X.M.; He, J.; Liu, M.X.; Morrision, A.M.; Wu, Y.Q. Building rural public cultural spaces for enhanced well-being: evidence from China. *Local Viroment*.**2024**,29,540-564. DOI: 10.1080/13549839.2024.2306593
28. Zheng, F.H. Comprehensive Rural Revitalization: Government Performance Targets and Farmers' Sense of Acquisition. *China Social Science*.**2023**, (03):136-150+207(in China).
29. Qu, Y.B.; Dong, X.Z.; Zhan, L.Y.; Zhu, W.Y.; Wang, S.; Ping, Z.L.; Zhang, B.L. Achieving rural revitalization in China: A suitable framework to understand the coordination of material and social space quality of rural residential areas in the plain. *Growth and Change*.**2021**,53,1052-1081.DOI10.1111/grow.12536
30. Liu, X.D.; Zhang, J.C.; Zhou, Z.C.; Feng, Z.Y. Investigating the Impact of Environmental Graphics on Local Culture in Sustainable Rural Cultural Tourism Spaces. Sustainability .2023,15,10207. DOI10.3390/su151310207
31. Wei, K.L.; Wang, W.L.; Fahad, S. Spatial and temporal characteristics of rural livability and its influencing factors: implications for the development of rural revitalization strategy. *Environmental Science and Pollution Research*.**2023**,30,49162-49179.DOI10.1007/s11356-023-25748-5
32. Sun, J.X.; Zhang, S.Q.; Ji, M.J. Revisiting the impacts of tourism from the perspective of social space production: an ethnological study of the Muslim community in Sanya, Hainan Province, China. *Current Issues In Tourism*.**2020**,23,1845-1863. DOI: 10.1080/13683500.2019.1653266
33. Shen, J.; Chou, R.J. Cultural Landscape Development Integrated with Rural Revitalization: A Case Study of Songkou Ancient Town.*Land*.**2021**,10,406. DOI: 10.3390/land10040406
34. Lu, Y.H.; Qian, J.X. Rural creativity for community revitalization in Bishan Village, China: The nexus of creative practices, cultural revival, and social resilience. *Journal of Rural Studies*.**2023**,97, 255-268. DOI: 10.1016/j.jrurstud.2022.12.017

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Sustainable Development in the Renovation of Historical Buildings: the Example of the Panoffs' Mansion in Wuhan

Xinyu Li [a,*]

[a] *University Pantheon-Sorbonne Paris 1, Paris, France*

KEYWORDS

urban Renewal,
Heritage building,
Energy-saving renovation,
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China,
Wuhan

ABSTRACT

This study examines the energy-efficient transformation of Panoffs' Mansion in Wuhan, integrating sustainability into urban renewal while preserving historical integrity. Through a qualitative methodology, the research employs field observations, literature reviews, and case studies. It explores how adaptive reuse of heritage structures can meet contemporary energy standards and urban demands, balancing preservation with modernization. This approach illuminates the potential of sustainable practices in revitalizing historical buildings, promoting a model for low-carbon urban development.

1. Introduction

In recent discussions on urban planning, the focus is increasingly on urban renewal and sustainable development as strategies to address the rapid pace of global urbanization. According to Roberts (2000), urban renewal is designed to enhance the economic vitality of cities and improve residents' quality of life by redeveloping areas with decaying, outdated, or nonfunctional buildings [1]. Its aim is to revitalize the city, addressing issues such as land, air, and water degradation, infrastructure obsolescence, housing shortages, and income or social segregation. However, traditional approaches to urban renewal have often emphasized physical renovation over broader concerns related to environmentally sustainable, socially inclusive, and economically viable regeneration [2].

Sustainable development, defined in the 1987 Brundtland Report, seeks to meet current needs without compromising the ability of future generations to meet theirs [3]. This approach calls for integrated planning that respects environmental integrity, economic stability, and social equity during urban renewal efforts. This shift in perspective has encouraged urban and transport planning to evolve from a one-dimensional to a multi-dimensional approach that includes green building, low-carbon strategies, public transit improvements, and the creation of vibrant centers to foster sustainable urban environments [4].

The challenges of rapid urbanization, particularly in developing countries, are compounded by environmental concerns, financial constraints, weak infrastructure, and high demographic growth, which make sustainable development even more challenging from an environmental and carbon emissions standpoint [5]. It is crucial for these regions to adopt holistic, low-carbon urban renewal approaches that address the nature of urban expansion, associated environmental challenges, and foster socioeconomic development [6].

China, as the most populous country and the world's second-largest economy, has experienced significant urbanization in recent decades, leading to severe environmental issues such as pollution

* Corresponding author at: University Pantheon-Sorbonne Paris 1, Paris, France.
E-mail address: komslee@gmail.com(Xinyu Li)

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and resource depletion [7]. A pivotal policy shift in 2013 saw the Chinese government incorporate eco-civilization into its national strategy, aiming to balance economic growth with environmental preservation [8]. This led to the aggressive promotion of "Green Building Evaluation Standards" across many cities in China to ensure that urban renewal projects adhere to environmental sustainability standards. These standards focus on energy efficiency, material conservation, and environmental friendliness, thus transforming old residential districts into ecological mixed spaces [9].

This research establishes the connection between urban renewal and sustainable development from multiple perspectives, particularly focusing on historical buildings as elements of energy-efficient renewal. Against this backdrop, the study employs a multi-dimensional methodological framework consisting of literature review, case studies, and empirical data analysis to explore the benefits and challenges of energy-efficient renovation of historical buildings, thereby advancing empirical knowledge of sustainable urban renewal strategies.

2. Literature Review

2.1. Challenges and Practices of Energy-Saving Urban Renewal

Urban renewal refers to the redevelopment and reconstruction of deteriorated, outdated or inefficient urban areas, with the purpose primarily of improving urban functions as well as increasing quality of human life [10]. This process is intended to solve a myriad of problems with urban development in general, such as environmental pollution, deteriorating infrastructure, and housing shortages or social isolation. Thus, the redevelopment of place in traditional urban renewal approaches stresses physical space interventions and frequently overlooks the integrated dimensions of environmental protection, social justice, and economic viability [11]. Building low-carbon cities is now a strategic direction for urban regeneration work. The concept of low-carbon cities is designed to mitigate carbon emissions and improve energy efficiency via utilization of renewable energies while minimizing environmental externalities.

In order to achieve the low carbonization of cities, measures like green buildings and sustainable districts should be developed [12]. Singapore, for example, is considered a global leader in the green building market with its strong architectural heritage and financial incentives such as governmental subsidy which helps it to quickly step-up development of green buildings through anamorphosis building standard [13]. Copenhagen likewise having introduced a highly workable energy-saving building system, has dramatically lowered urban carbon emissions, showing the path to "sustainable cities" on a global scale [14].

Government, in this respect, takes an irreplaceable role by setting up and enforcing related policies and regulations as well the mandatory legal, and financial supports to renew the urban habitats [15]. But the exact problems and hurdles faced in policy implementation differ by country and region. Research focusing on how best to tailor and adapt national policies to local contexts is very necessary with substantial scope for more depth in investigation Green building and low-carbon design should be further integrated with urban renewal in a more systematic way to achieve both environmental improvement and economic profit [16]. Furthermore, this is an important area to examine the implementation of urban renewal policies and sustainable development as well.

The characteristics of low-carbon and sustainable development have been incorporated into the urban renewal process in China in recent years. The Chinese government has facilitated and implemented these initiatives [17]. Beijing is also a city that has been making substantial efforts in urban renewal with low-carbon focus. The government provides subsidies, after all new buildings' standards of energy consumption, and has set strict limits of energy consumption, while for the loss facilities the restrictions were mainly in existing buildings [4].

The last observation indicates disparities in resource distribution and policy implementation across regions are still prevalent. For example, the adoption and enforcement of strict environmental standards is often constrained in smaller cities and economically less developed areas because of their limited financial resources and technological capacities [18].

2.2. Integrating Sustainability and Cultural Heritage: Preservation and Development

The preservation of historic districts represents a complex yet essential endeavor that necessitates a meticulous balance between maintaining cultural heritage, modernizing urban functionality, and meeting the evolving needs of contemporary society [19]. Historic district preservation is based on certain principles to ensure that the originality and cultural significance of a place are retained without compromising the needs for modern urban development. International guidelines, such as the Venice

Charter (1964) and the Prague Charter (1976), underline the preservation of original forms and historical contexts, while accommodating modern uses of structures [20]. This preservation strategy helps not only in protecting the historical memory and cultural heritage of urban context, but also in enhancing the quality of urban life by providing rich cultural experiences.

Preservation of the historic districts depend on building renovation and is one of the vital elements. The buildings can be updated to function better and be safer without losing the aesthetic that comes with maintaining history. The energy-efficient buildings and sustainable designs are now used on modernized urban areas in recent past [21]. The Marais district of Paris offers an example of how these can be carefully exchanged. One in which this district has been able to preserve its history and culture, whilst growing into a lively cultural and commercial center [22], Such projects as the renovation of the Parisian Marais district saw the Parisian government work to maintain a majority of historical buildings and enhance public parks, infrastructure, and environmental quality, thus simultaneously encouraging sustainability and cultural preservation.

Modern technology and materials also have an important part to play in construction- apart from preservation and renovation. Synthetic materials and modern technology can make buildings both safe and functional while retaining their historical integrity [23]. Glass and steel structures when used can add to the strength of a building; however, they also allow for better light and improve natural ventilation [24]. Also, energy can be conserved properly by the use of solar panels, rainwater recharging system and saving devices are installed and make heritage buildings eco-friendlier and more sustainable [25].

China has had the most extensive history of culture for preservation, and its achievements in the preservation of historic districts are a combination of traditional conservation practices and modern sustainable development ideas [26]. These include the preservation work in the ancient city of Suzhou, celebrated for its classical gardens and the creative preservation policies in Beijing's Hutongs which respect historic preservation alongside modern urban needs [27], [28]. These initiatives reflect China's commitment to preserving its cultural heritage while promoting sustainable urban development.

However, the research landscape in China also reveals several challenges. These include an inadequate incorporation of low-carbon, environmentally friendly technology into preservation practices and the lack of a cohesive legal system framework [4]. Researchers call for a more expanded perspective that captures the range of contemporary developments in green technologies [29].

3. Methods

Wuhan, the capital of Hubei Province, is a pivotal city in central China, often dubbed the "Thoroughfare of Nine Provinces" due to its strategic role as a transportation and industrial hub. With a rich history spanning over 3,500 years, Wuhan has long been a significant commercial and industrial center. The city's unique geographic and urban landscape is shaped by the confluence of the Yangtze and Han Rivers [30].

Historically, Wuhan was a locus for foreign concessions, where various Western powers set up enclaves for trade and residency during the late 19th and early 20th centuries [31]. Following the Second Opium War, Hankou became a concession area for Western powers, beginning from Jianghan Road and extending along the river [32].

Panoffs' Mansion stands out in the former concession area of Hankou, boasting a land area of 3,998 square meters and a base area of 2,368 square meters, with a building density of 59.4% and a total building area of approximately 9,423 square meters. During the same era, a typical plot in the Russian Concession measured about 2,000 square meters, with most blocks divided into 5 to 10 plot units, except for industrial estates. Panoffs' Mansion is unique as the only non-industrial building that occupies an entire block [33].

Located at a Y-shaped intersection, Panoffs' Mansion follows a triangular plot layout, a shape uncommon in Chinese cities but frequently seen in Western urban planning, where radial roads and triangular or fan-shaped blocks with acute angles are prevalent, as shown in Figure 1. Western architects often design buildings on acute-angled plots with arcs or truncated corners, a feature reflected in the design of Panoffs' Mansion.

This study aims to explore the transformation of this historic building. It examines how authorities managed to convert a dilapidated residential building into a historic heritage site that meets modern needs and energy efficiency standards following its restoration.

Methodologically, this research employs a qualitative approach, including resource analysis of writings and fieldwork observations. Conducted in 2024, the fieldwork involved two months of non-intrusive observations of the building's exterior and public spaces, alongside content analysis of web-

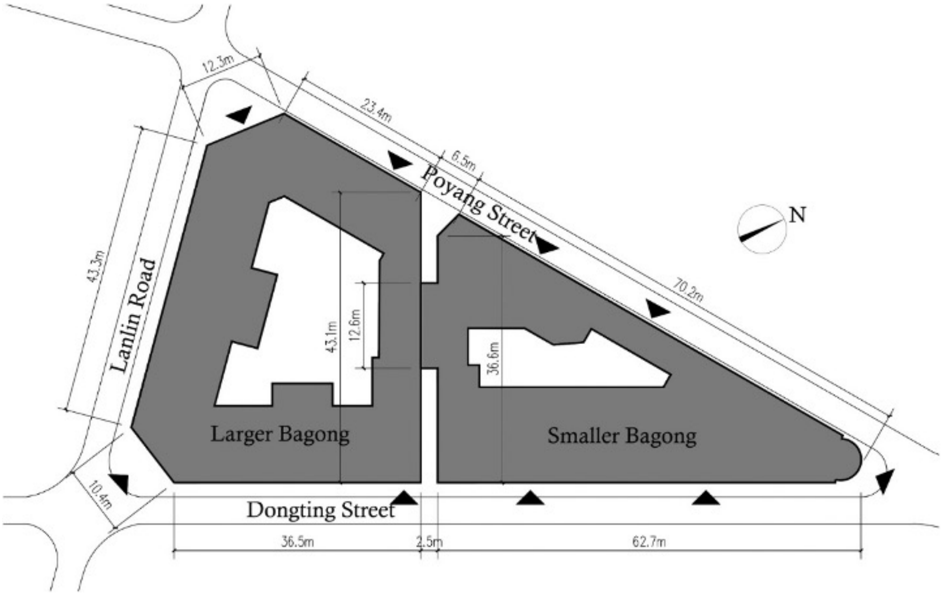

Fig. 1. Plan map of Panoffs' Mansion

based materials and official documents. This blend of methods provides a comprehensive, multidisciplinary perspective on the subject.

4. Results

4.1. Architectural history and characteristics

Panoffs' Mansion, the largest high-grade apartment in Hankou during the late Qing Dynasty and early Republic of China, is a landmark in the former Russian Concession of Jiang'an District, Wuhan, China. This building, a pioneer of apartment living in Wuhan, represents the earliest example of collective residence architecture in Hankou and typifies modern collective living from that era. Since its construction, the building has witnessed the handover of the Hankou concession and the establishment of the People's Republic of China, with numerous changes in its residents [33].

Constructed in 1901 by Russian tea merchant J.K. Panoff, the building is situated at Poyang Street. The actual designer remains unknown, though sources suggest it might be Hemmings & Berkley or a Russian architect. The structure was developed in two phases: the larger section on Lanling Road known as "Larger Bagong" was completed first in 1910, followed by the "Smaller Bagong" on Lihuangpi Road, recognized for its smaller size.

Panoffs' Mansion is built from masonry with a wooden structure, featuring three floors above ground and one below. It combines Russian ethnic characteristics with romantic elements prevalent in the European classical revival style of that period. The building is notably triangular, with a hall on the third floor resembling a monk's hat, earning it the nickname "Russian head tip."

Fig. 2. Photo of Panoffs' Mansion in the 1920s

This building features a distinctive Russian-style dome at the corner and cantilevered balconies along the street-facing façade, as seen in Figure 2. The architecture primarily exhibits the classical revival style popular in Europe at the time, characterized by the repetition of motifs on the façade, with a strong emphasis on proportion and symmetry. This style also extends to the interior, where the layout strives for symmetry, incorporating classical elements such as columns and arches [34].

Additionally, the building incorporates features of the colonial style, notably exterior porches that serve as balconies or corridors connecting different units. This architectural style originated from colonizers in Southeast Asia, designed to adapt to the region's hot and humid climate. As it spread to the concessions of major Chinese cities, it became one of the first Western architectural styles to influence local designs.

4.2. Lack of maintenance of historic buildings

Due to a shortage of living space, modifications were made over time: interior balconies were enclosed, rooms were subdivided, and mezzanines were added to maximize space. Despite these adaptations, overcrowding was a significant issue even before these changes, as described in a 1947 Yishi Newspaper article that portrayed the dense and cramped conditions, with potentially thousands of residents at one time [33].

Following the founding of the People's Republic of China in 1949, the building was nationalized and allocated to bank employees as public housing. In response to ongoing space shortages, an additional story was added in 1964. The new top floor is three meters high, contrasting with the original floors' heights of 4.3 and 3.8 meters. In the renovation, Smaller Bagong maintained the original red plain brick style, whereas Larger Bagong's addition was covered with cement mortar, creating a stylistic divergence in the building's facade and overall appearance.

The additional storey, while providing some relief, could not adequately accommodate the growing number of inhabitants, resulting in excessive wear and tear on the building's infrastructure (Figure 3). This continuous overuse has exacerbated the deterioration of both its interior and exterior. The hallways and staircases, designed for far fewer occupants, now bear the marks of decades of overcapacity, showing signs of structural fatigue and neglect. Furthermore, the repeated subdivision of rooms compromised the building's original architectural integrity, leaving many areas poorly ventilated and inadequately lit, which diminished the quality of living conditions significantly.

Moreover, the lack of regular maintenance has left the building in a dilapidated state. The facade, once a testament to architectural elegance, now displays a patchwork of mismatched materials and styles, reflecting the piecemeal repairs that have failed to preserve its historical character [34]. Inside, the situation is no better, with cracked plaster, peeling paint, and outdated electrical systems that pose safety risks to the residents. The heritage's historic charm and structural stability have been severely compromised, calling for urgent comprehensive restoration efforts to salvage and restore it to its former glory, both as a protected heritage building and as a useful modern space.

Fig. 3. Panoffs' Mansion in the 2010s with dilapidated infrastructure

4.3. Sustainable design renovation project

Promoting low-carbon living is crucial, particularly through the retrofitting and construction of buildings adhering to green and low-carbon standards. The renovation of Panoffs' Mansion employed energy-saving technologies and sustainable materials to enhance energy efficiency and reduce emissions, while preserving its original appearance. The installation of LED lighting and improvements in thermal insulation were key focuses. By enhancing wall, roof, and window insulation, heat loss in winter and cooling needs in summer were minimized, reducing the overall energy demand for climate control. These enhancements not only saved significant energy but also improved the indoor comfort for both residents and businesses.

The preservation and restoration of this historic building began in 2018. Experts from the China International Trust and Investment Corporation (CITIC) Design & Research Institute conducted comprehensive on-site surveys, data collection, and consultations to accurately restore the building's original form and materials. Structural reinforcements were made to adapt the building to new uses while preserving its architectural integrity. "Determining the original architectural form and dealing with the many later modifications added a layer of complexity to the restoration," experts noted. The

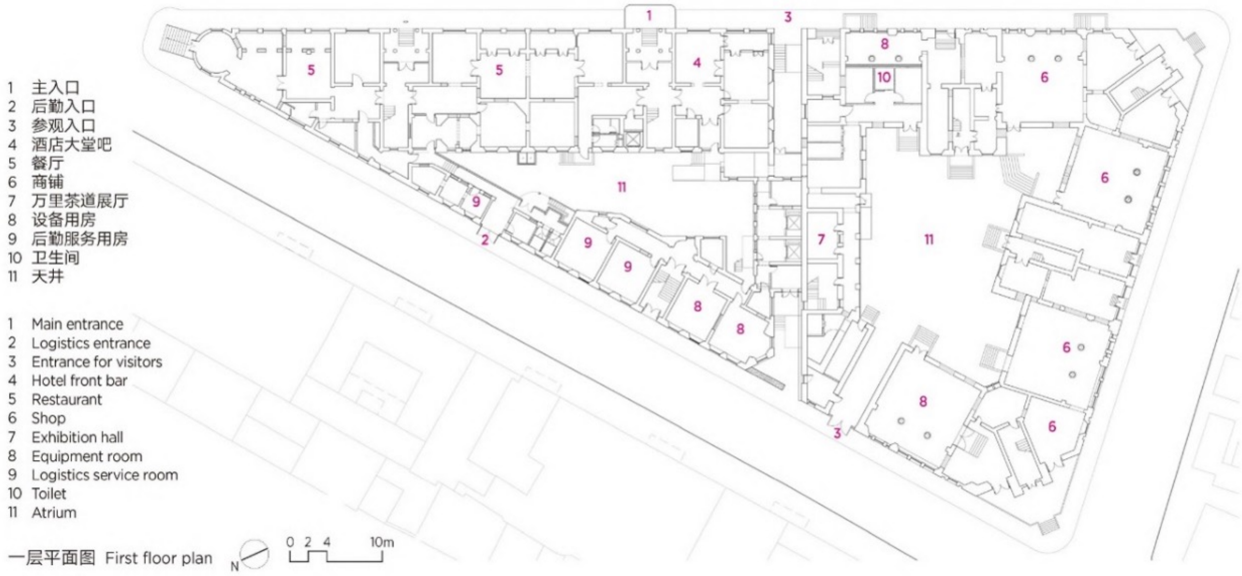

Fig. 4. First floor plan of Panoffs' Mansion after the rehabilitation project

building now serves as a commercial and cultural hub, featuring exhibition spaces that highlight its history, as well as culturally themed restaurants and a hotel. The redesign also transformed two patios into open spaces to facilitate better air circulation and public interaction, as shown in Figure 4.

The project embraced green and sustainable design principles, using integrated solutions for ventilation, sun shading, and thermal insulation, supported by Building Information Modeling (BIM) technology for precise supervision of design and construction. The "3R" principle—recycle, reuse, and renew—guided the selection of materials, favoring those that matched the original in utility while promoting resource sustainability (Figure 5). "Extensive pre-construction trials and discussions ensured the appropriateness of materials and methods." the team explained. This approach not only reduced the project's carbon footprint by limiting energy-intensive production but also extended the lifecycle of materials, supporting a circular economy.

4.4. Interior renovation complying with energy-saving standards

In terms of energy efficiency, particular attention was given to the thermal insulation performance of the building's envelope, crucial in regions with hot summers and cold winters. The project utilized innovative internal insulation techniques and 3R materials to enhance the thermal performance of facades and other key elements without compromising the building's historical façade. The use of double-pane LOW-E insulated windows and strategically placed louvers reduced unnecessary solar heat gain, maintaining the building's aesthetic while enhancing its energy efficiency. Environmental simulations of these materials helped achieve thermal coefficients well within the local energy-saving standards for Wuhan, significantly lowering the building's heating and cooling requirements.

According to simulation calculations Table 1, the thermal coefficients (K-values) for the exterior walls and the roof of the remodeled building envelope were simulated at 0.51 W/(m²·K) and 0.35 W/(m²·K), respectively. When compared with the Wuhan building energy-saving design standards, these values fall within the acceptable ranges. By

Table 1. Simulated thermal coefficient calculation

Building structure	Simulated building Coefficient W/ (m²·K)	Wuhan Municipal Energy Conservation Design Standard Coefficient W/ (m²·K)
Roof	0.35	0.40
Exterior walls	0.51	0.70
Windows	1.80	2.00

Fig. 5. Details of the renovated building facade

incorporating these environmentally friendly materials and technologies, we can significantly reduce the energy required for heating and cooling, thereby decreasing carbon emissions. This approach not only aligns with sustainable building practices but also contributes to broader environmental protection goals.

Additional sustainable features include rainwater harvesting, high-performance air conditioning systems with heat recovery, and rooftop solar panels, which collectively decrease the building's dependence on conventional energy sources and enhance its overall sustainability. Intelligent lighting systems further reduce the building's energy consumption.

Today, Panoffs' Mansion is not only a preserved cultural landmark in Wuhan but also a popular tourist destination, as shown in Figure 6. These renovations have successfully extended the life of this historic building, aligning it with modern environmental and energy standards while maintaining its historic charm. The project's recognition with the Berlin Better Future Award underscores its significance and the growing public and official interest in sustainable restoration practices.

Fig. 6. Historical buildings are now popular tourist destinations

5. Conclusion and Limitations

This research underscores the dynamic interplay between historical preservation and modern sustainability through the renovation of Panoffs' Mansion in Wuhan. The project exemplifies how integrating sustainable design within urban renewal initiatives can effectively enhance energy efficiency and foster environmental stewardship while safeguarding cultural heritage. By implementing cutting-edge green technologies and adaptive reuse strategies, the initiative not only preserved the heritage's historical integrity but also transformed it into a beacon of low-carbon living.

The broader impact of this project extends beyond architectural conservation, stimulating local economic growth. The transformation of Panoffs' Mansion into a vibrant, multifunctional space has contributed to the revitalization of the surrounding area, promoting it as a cultural and tourist hub. This has, in turn, bolstered public interest and investment in sustainable urban development, highlighting the potential for heritage sites to lead urban innovation.

Moreover, the project serves as a valuable case study for similar initiatives worldwide, providing insights into the challenges and opportunities of marrying historical preservation with sustainability goals. The successful implementation in Wuhan demonstrates the practicality of such endeavors, encouraging other cities to consider sustainable practices in their urban renewal efforts.

However, the study's findings are tempered by certain limitations. The unique architectural and historical context of Panoffs' Mansion means that the specific strategies employed may not be directly applicable in different settings, where varying cultural, environmental, and regulatory conditions may affect the feasibility of similar interventions. Additionally, the research was primarily qualitative, focusing on observational and case study data which, while rich in detail, might lack the empirical rigor provided by quantitative methods.

Future studies could enhance the robustness of findings through mixed-methods approaches, incorporating statistical analyses to quantify the environmental and economic impacts of renovation projects. This would provide a more comprehensive evidence base to support the scalability of sustainable urban renewal strategies across diverse global contexts.

References

1. P. Roberts, "The evolution, definition and purpose of urban regeneration," *Urban regeneration: A handbook*, vol. 1, pp. 9–36, 2000.
2. H. W. Zheng, G. Q. Shen, and H. Wang, "A review of recent studies on sustainable urban renewal," *Habitat international*, vol. 41, pp. 272–279, 2014.
3. M. Hajian and S. J. Kashani, "Evolution of the concept of sustainability. From Brundtland Report to sustainable development goals," in *Sustainable resource management*, Elsevier, 2021, pp. 1–24.
4. G. W. Hunter, G. Sagoe, D. Vettorato, and D. Jiayu, "Sustainability of low carbon city initiatives in China: A comprehensive literature review," *Sustainability*, vol. 11, no. 16, p. 4342, 2019.
5. A. Aliyu and L. Amadu, "Urbanization, cities, and health: the challenges to Nigeria–a review," *Annals of African medicine*, vol. 16, no. 4, pp. 149–158, 2017.
6. X. He *et al.*, "Implementation plan for low-carbon resilient city towards Sustainable Development Goals: challenges and perspectives," *Aerosol and Air Quality Research*, vol. 20, no. 3, pp. 444–464, 2020.
7. P. Wu and M. Tan, "Challenges for sustainable urbanization: a case study of water shortage and water environment changes in Shandong, China," *Procedia Environmental Sciences*, vol. 13, pp. 919–927, 2012.
8. M. Marinelli, "How to build a 'Beautiful China'in the Anthropocene. The political discourse and the intellectual debate on ecological civilization," *Journal of Chinese Political Science*, vol. 23, no. 3, pp. 365–386, 2018.
9. W. Pan and J. Du, "Towards sustainable urban transition: A critical review of strategies and policies of urban village renewal in Shenzhen, China," *Land Use Policy*, vol. 111, p. 105744, 2021.
10. N. Ezeadichie and C. John-Nsa, "Sustainable urban renewal: planning or people oriented?," *Journal of Environmental Management and Safety*, vol. 12, no. 1, pp. 17–17, 2021.
11. K. Bradley, "Just environments: politicising sustainable urban development," PhD Thesis, KTH, 2009.
12. W. Drożdż, G. Kinelski, M. Czarnecka, M. Wójcik-Jurkiewicz, A. Maroušková, and G. Zych, "Determinants of decarbonization—how to realize sustainable and low carbon cities?," *Energies*, vol. 14, no. 9, p. 2640, 2021.
13. H. Han, "Governance for green urbanisation: Lessons from Singapore's green building certification scheme," *Environment and Planning C: Politics and Space*, vol. 37, no. 1, pp. 137–156, 2019.
14. T. Beatley, Green Cities of Europe-Global Lessons on Green Urbanism. Island press, 2012.
15. M. Priyanta and C. S. A. Zulkarnain, "Urban green open space in developing countries: Indonesia regulations, problems and alternative solutions," *Journal of Property, Planning and Environmental Law*, vol. 16, no. 2, pp. 134–151, 2024.
16. L. Chen *et al.*, "Green construction for low-carbon cities: a review," *Environmental chemistry letters*, vol. 21, no. 3, pp. 1627–1657, 2023.
17. M. Radulescu, J. Cifuentes-Faura, K. Si Mohammed, and H. Alofaysan, "Energy efficiency and environmental regulations for mitigating carbon emissions in Chinese Provinces," *Energy Efficiency*, vol. 17, no. 6, p. 67, 2024.
18. H. Yi and Y. Liu, "Green economy in China: Regional variations and policy drivers," *Global Environmental Change*, vol. 31, pp. 11–19, 2015.
19. Z. Qian, "World Heritage Site inscription and waterfront heritage conservation: evidence from the Grand Canal historic districts in Hangzhou, China," *Journal*

of Heritage Tourism, vol. 16, no. 6, pp. 684–704, 2021, doi: 10.1080/1743873X.2020.1828894.

20. M. Ripp and D. Rodwell, "The geography of urban heritage," *The Historic Environment: Policy & Practice*, vol. 6, no. 3, pp. 240–276, 2015.

21. D. Rodwell, Conservation and sustainability in historic cities. John Wiley & Sons, 2008.

22. T. Freytag and M. Bauder, "Bottom-up touristification and urban transformations in Paris," *Tourism Geographies*, vol. 20, no. 3, pp. 443–460, 2018.

23. C. Kibert, Sustainable construction: green building design and delivery. John Wiley & Sons, 2016.

24. S. Sadineni, S. Madala, and R. Boehm, "Passive building energy savings: A review of building envelope components," *Renewable and sustainable energy reviews*, vol. 15, no. 8, pp. 3617–3631, 2011.

25. P. Ombati, "Evaluating Awareness Levels and Barriers to Green Building Implementation," PhD Thesis, University of Nairobi, 2023.

26. J. Whitehand and K. Gu, "Urban conservation in China: Historical development, current practice and morphological approach," *Town Planning Review*, vol. 78, no. 5, pp. 643–670, 2007.

27. X. Ma and B. Wu, "Cooperation of Protection, Renovation of Historic Streets and Sustainable Development of Tourism: A Case Study of Dazhalan Area in Beijing," *Urban Plan*, vol. 9, pp. 49–54, 2005.

28. M. Orlenko *et al.*, "The specificity of the restoration and monument protective measures for the preservation of historical Chinese Gardens," *International journal of conservation science*, vol. 12, no. 3, pp. 1003–1026, 2021.

29. S. E. Bibri and J. Krogstie, "Smart sustainable cities of the future: An extensive interdisciplinary literature review," *Sustainable cities and society*, vol. 31, pp. 183–212, 2017.

30. S. Han and X. Wu, "Wuhan," *Cities*, vol. 21, no. 4, pp. 349–362, 2004, doi: 10.1016/j.cities.2004.03.007.

31. S. Cheng, Y. Yu, and K. Li, "Historic conservation in rapid urbanization: a case study of the Hankow historic concession area," *Journal of Urban Design*, vol. 22, no. 4, pp. 433–454, Jul. 2017, doi: 10.1080/13574809.2017.1289064.

32. X. Li, "Cultural heritage and modernization: the evolution of Lifen neighborhoods in Wuhan," *Urban, Planning and Transport Research*, vol. 12, no. 1, 2024, doi: 10.1080/21650020.2024.2409683.

33. X. Liu, J. Yang, and Q. Tong, "The forerunner of modern collective residence in Hankou: the study on Panoffs' Mansion," *Journal of Asian Architecture and Building Engineering*, vol. 22, no. 5, pp. 2460–2489, 2023.

34. Z. Zhang, Y. Zou, and W. Xiao, "Exploration of a virtual restoration practice route for architectural heritage based on evidence-based design: a case study of the Bagong House," *Heritage Science*, vol. 11, no. 1, p. 35, 2023.

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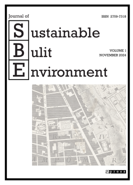

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Research on Optimization of Industrial Building Facades Integrating With Photovoltaic Power

Hailong Chai [a,*,†], Jingya Zeng [b,†]

[a] *Department of Architecture and Urban Studies, Politecnico di Milano*
[b] *School of Geography, Queen Mary University, London*

KEYWORDS

industrial Buildings,
photovoltaic,
industrial Facade;
building integrated photo-voltaic(BIPV),
CdTe Photovoltaic Glasses

ABSTRACT

Industrial buildings are important production carriers in urban space, but they also have problems such as high production energy consumption, serious environmental pollution, and poor built interface, which have attracted much attention. Building environment optimization and energy structure adjustment have become the focus of industrial building research. In the context of the national carbon neutral policy, this paper studies the impact of industrial buildings on the urban environment, combines photovoltaic power generation technology, explores the integrated design strategy of CdTe generation glass and industrial building facades, and uses the southwest cement plant project in Lijiang, Yunnan as an example, a practical study was carried out, aiming to use industrial building facade resources to improve the aesthetics and functionality of the building facade at the urban interface of the park. Research shows that the strong plasticity of CdTe photovoltaic glass can not only provide necessary power energy for industrial buildings and optimize the building's energy structure, but its color and material ductility can also improve the aesthetics of industrial building facades. This article provides certain reference and reference significance for subsequent related research.

1. Introduction

According to research by the international research agency IEA, China's industrial sector ranks second among all industries with a 36% share of carbon emissions, second only to the energy production industry with a 48% share. The "2022 China Building Energy Consumption and Carbon Emissions Research Report" points out that in 2020, the total energy consumption of Chinese buildings was 2.27 billion tce, and the total carbon emissions of buildings were 5.08 billion tCO^2. Among them, the energy consumption and carbon emissions in the production stage of building materials, mainly cement and steel, accounted for 22.3% and 28.2% of the total, respectively. The "Implementation Plan for Carbon Peaking in the Industrial Sector" released by China states that by 2025, the energy consumption of industrial units above designated size will decrease by 13.5% compared to 2020. In the "3060" target, by 2060, China's industrial carbon dioxide emissions will decrease by nearly 95%, the use of coal without emission reduction technologies will decrease by 90%, and the remaining emissions will be offset by negative

* Corresponding author at: Department of Architecture and Urban Studies, Politecnico di Milano, P.zza Leonardo da Vinci 26, 20133 Milano, Italy.
E-mail address: chai_1988@126.com (Hailong Chai)
† These authors contributed equally to this work.

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emissions from the power and fuel conversion industries. Therefore, in the important period of China's transition from an incremental economy to a stock economy, the transformation of brownfield industrial buildings has become one of the important components of the transformation, and it is urgent to promote the adjustment of building energy structure with industrial buildings as the core.

In recent years, the development of the photovoltaic industry has received increasing attention from the country, and photovoltaic have also been regarded as one of the main strategies to achieve the national "dual carbon" goals. In the national "The 14th Five-year Plan" for the development of renewable energy, it is explicitly stated to "vigorously promote the development of wind and photovoltaic power bases" and "actively promote the distributed development of wind and photovoltaic power generation". Compared with the rapid rise of photovoltaic manufacturing, the launch of China's photovoltaic terminal application market is significantly lagging behind*(Wang Hongwei, Zhu Xueting,Yin Chenxi ,2022)*. At present, the application of PVs is still mainly focused on centralized photovoltaic power stations and distributed energy stations. However, this type of power station requires a large amount of land resources as a carrier, and cannot be widely promoted in urban spaces with tight construction land. With the emergence of thin-film cells, various application scenarios of photovoltaic cells have begun to appear in urban spaces, and photovoltaic building integration technology has emerged. However, the integrated technology of photovoltaic buildings in China is still in its infancy, and its applications are mainly concentrated in residential buildings, public buildings, office buildings, and landscape ornaments. There are few studies and cases related to the integrated design of photovoltaic modules and industrial buildings.

The innovation of this article lies in the integration of photovoltaic building technology, focusing on the energy structure adjustment and facade optimization of productive industrial buildings, and exploring the technical path of combining photovoltaic modules with industrial buildings. On the one hand, by utilizing the strong plasticity of cadmium telluride (CdTe) photovoltaic glass, the overall texture of industrial building facades was stitched together, improving the production environment and appearance of industrial buildings; On the other hand, fully utilizing the idle facade space resources of industrial buildings, constructing distributed photovoltaic power stations, empowering buildings and parks, and promoting the energy structure adjustment of buildings and even parks.

2. Literature Review

2.1. Research on Industrial Architecture and Heritage

In the context of the current climate crisis, research on industrial architecture and related fields in China mainly focuses on three aspects: planning and design strategies for new industrial parks, investigation and evaluation of industrial heritage, and spatial and functional transformation of industrial heritage. At the level of design strategies for industrial buildings, scholars are enthusiastic about using sustainable and green building design theories to study new industrial parks and their architectural spaces. Scholars have integrated low-carbon and sustainable concepts into industrial building design, and proposed design foundation suggestions for industrial buildings from three levels: cultivating industrial rootedness, researching park ecology, and sustainable industrial building design (*Wangyi,Chenjing,2008*). Modular and modular design is beneficial for controlling carbon emissions throughout the entire lifecycle of industrial buildings, in order to achieve energy-saving and emission reduction goals(*Yang Chunhong,Pu Yunyun,2023*). Scholars have proposed the use of BIM technology to construct a digital information model for industrial buildings, in order to achieve the goal of innovative transformation of existing industrial building spaces, in response to issues such as poor access ports for industrial heritage informationization(*Deng Yuanyuan,Lihan,Yangnan,Zhu Yiwen,2023*).

In addition, China has a large amount of industrial heritage resources, and scholars' investigation, research, analysis, and evaluation of industrial heritage have laid a solid foundation for the renewal and transformation of China's industrial heritage. Non industrial transformation of existing industrial buildings is currently the main transformation strategy, which mainly studies and evaluates the spatial form of existing industrial building structures from the perspectives of architecture and structure, in order to introduce new functional formats(*Liu Boying,Hu Rongrui,Lirong,2018*). The transformation model of industrial heritage based on the theory of symbiosis explores the strategies of industrial architecture in achieving cultural symbiosis, pattern symbiosis, and environmental symbiosis through symbiosis in different eras, different buildings, and different activities(*Gao Changzheng,Yanfang,Long*

Wenyan,2017). Based on the theory of spatial production, this study investigates the morphological evolution of historical industrial spaces in Chinese cities, mainly focusing on the influencing factors in the transformation process of industrial building spaces, and can analyze the laws of typical industrial space transformation, cultural transformation, and functional transformation(*Huanglei,2023*). A quantitative evaluation of the vitality of Tianjin's industrial heritage was conducted using diverse data from dimensions such as cultural vitality, social vitality, economic vitality, and population vitality. Based on the research results, renovation strategies were proposed from three levels: spatial quality, functional replacement, and facility layout (*Ren Binbin,Wang Jingshuang,Xiao Shaoying,2023*).

The spatial and functional transformation of industrial heritage is an important means of testing research results. Practice mainly combines the historical value, aesthetic value, and spatial value of industrial relics to revitalize and utilize abandoned industrial buildings. This type of research mainly focuses on the practice of industrial building renovation. Based on more than 10 years of industrial heritage engineering practice in *Jingdezhen*, some scholars have proposed a technical system consisting of four dimensions: inheritance and protection, coexistence of old and new, functional adaptation, and green enhancement, to support the protection and utilization of industrial heritage(*Zhangjie,Li Minhua,Xieyang,2023*). The renovation of the former site of *Huaxin* Cement Plant in *Huangshi* City, Hubei Province, explores the planning strategies for industrial heritage protection in the urban center from three aspects: protection concept, functional configuration, and utilization mode(*Liuna,Huang Jingnan,Zhoujun,2023*). Based on the concept of "fiber block", spatial integration and functional activation were carried out on the industrial heritage style, lane historical style, and historical protected buildings of Shanghai *Binjiang*. Spatial definition and design guidance strategies were proposed from six dimensions: scale, functionality, and density(*Lijian,Chen Changqing,Ma Xiyin,2021*).

2.2. Development of energy-saving technology in industrial buildings

Industrial building energy efficiency is different from traditional industrial energy efficiency technologies. Traditional industrial energy-saving technologies mainly focus on two aspects: equipment and energy. The energy-saving technologies discussed in this article mainly focus on the energy end. The core of industrial energy conservation is the conservation of electrical energy, which mainly focuses on the utilization of clean energy. The application of new energy technologies is manifested in the use of clean energy sources such as wind, solar, and geothermal energy. The utilization of solar energy is still at the stage of centralized energy stations. Centralized power stations feed back industrial energy by constructing large-scale power stations, utilizing clean energy for power generation, and delivering electricity to industrial parks through power infrastructure. This method does indeed reduce the electricity demand in urban areas, decrease the electricity load, and decrease the city's reliance on traditional energy sources. However, large-scale clean energy power plants require power transmission infrastructure, which requires a high level of infrastructure construction. The emergence of BIPV technology has enabled centralized energy stations to gradually transform into distributed ones. The so-called distributed power station refers to the establishment of power stations near the energy demand end to meet the small-scale usage needs in the vicinity. BIPV technology has the characteristics of small land occupation and nearby consumption, and requires less infrastructure for high-power power transmission.

2.3. Development of integrated photovoltaic building technology

The integration of photovoltaic technology with building utilization began in the mid-20th century, with Solar One becoming the first solar powered building. And China's solar roof plan, which began in 1996, has since opened up projects that combine solar energy with buildings. BAPV and BIPV are two ways of combining photovoltaic with building scenarios. BAPV (Building Attached Photovoltaic) is a passive photovoltaic application strategy that independently attaches distributed photovoltaic modules outside the building structure. With the development of photovoltaic technology, photovoltaic glass has begun to possess characteristics such as transparency and low light intensity, which can meet the requirements of building thermal performance and structural strength. Integrated photovoltaic building technology has begun to emerge. BIPV (Building Integrated Photovoltaic), also known as photovoltaic building integration, is an active design strategy that uses photovoltaic modules as building materials and integrates building design.

BAPV is a passive adaptation strategy in which photovoltaic modules are attached to buildings. BAPV is a combination of distributed photovoltaic modules and building surfaces, with photovoltaic panels fixed to the building (*Zhangjian,Xie Yingming,Yang Yuanhao,2017*). The two sides are independent and integrated, with clear boundaries. In this case, distributed photovoltaic modules are ancillary facilities of buildings. As an external installation device, photovoltaic modules provide electrical energy for buildings, while buildings provide spatial carriers for photovoltaic modules. Under this design strategy, photovoltaic modules are usually made of crystalline silicon photovoltaic materials and are commonly installed on building roofs, affecting the overall appearance of the building. In addition, centralized photovoltaic power plants require a large amount of land, and in the context of extremely scarce construction land resources, this technology is more commonly located in suburban areas of cities. Even as photovoltaic modules used as roofs, their dazzling effect can cause light pollution to urban spaces, and they cannot be organically integrated with buildings, resulting in visual damage, making them difficult to widely promote in urban spaces. BIPV, also known as photovoltaic building integration, is an active adaptive strategy for the integrated design of photovoltaic modules and buildings. In BIPV, photovoltaic modules appear in the form of a building material, and the photovoltaic array becomes an integral part of the building (*Huang Xinyu,Chenwen,2022*). With the gradual maturity of thin-film solar cell technology, photovoltaic modules can better participate in building structures and spaces. The integration of photovoltaic modules and buildings forms a symbiotic relationship. Photovoltaic modules cannot operate independently without buildings, and the building structure without photovoltaic modules is incomplete. Under this strategy, photovoltaic modules can already meet the relevant requirements of building materials in terms of structural strength, and their characteristics such as transparency, color, and texture can ensure the uniformity of building appearance.

3. Characteristics and problems of production-oriented industrial buildings

3.1. Review of China's Industrialization Process

Industrial buildings refer to the general term for buildings, structures, and industrial facilities engaged in various industrial production activities in urban activities. The main functions of buildings or facilities include production, equipment, storage, transportation, etc. On the one hand, when cities plan their land use, they usually consider the land value and industrial attributes, and allocate industrial land to the suburbs of the city. On the other hand, the industrial production content engaged in by industrial buildings may have potential problems such as noise pollution, dust pollution, and air pollution, which also result in the uniqueness of industrial building design. In summary, industrial buildings exhibit characteristics such as large building space scale, diverse combination forms, single function, and high energy consumption.

The development of industrial architecture is closely related to the industrialization process in China. China's industrial development can be divided into the primitive industrial period, the modern industrial period, and the modern industrial period*(Wang Yunke,2021)*. The primitive industrial period was before 1840, based on the traditional workshop style handicrafts of old China. The modern industrial period lasted from the Opium War to the establishment of New China. As the beginning of modern industrialization, since the Westernization Movement, due to the input of foreign technology, Chinese industry has grown from scratch, reflecting the characteristics of regional development.

The modern industrial stage can be divided into a period of recovery and a period of rapid development after the founding of the People's Republic of China. After the establishment of the People's Republic of China, with the "Third Front Construction" as the starting point, it has driven the vigorous development of industries in mainland China. After the reform and opening up, China's modern industry developed rapidly. A comprehensive industrial category system has been established, and a regional coordinated development strategy centered on industrial parks has led to rapid development of the industrial economy. Modern industrial parks have become the main feature, and industrial buildings are showing a trend of centralization.

3.2. Traditional Industrial Architecture and New Era Industrial Parks

The construction of industrial parks is an important strategic deployment since China's reform and opening up, and it is also one of the driving forces for China's economic development and urbanization. It should be clarified that the industrial park described in this article is different from an industrial park. At present, China's industrial parks have diversified industrial forms. After industrial transformation, China's industrial parks are developing towards new technologies and new economies. The industrial park mentioned in this article refers to a park with the secondary industry as its main content, which has the characteristics of remote geographical location, harsh production environment, high energy consumption, and high carbon emissions. According to the Catalogue of Review and Announcement of China Development Zones, in 2018, 219 national economic and technological development zones and 169 national high-tech industrial development zones, which mainly serve the function of carrying industrial clusters and represent typical industrial parks in China, achieved a total regional GDP of about 21.3 trillion yuan, accounting for 23.7% of the national GDP that year. The development process of industrial parks in China can be roughly divided into the following four stages:

1) *Initial and budding stage (1979-1991)*

In 1979, China's first industrial park, the China Merchants *Shekou* Industrial Park, was completed, marking the official beginning of the development of industrial parks in China. Under the background of reform and opening up and global industrialization, China has implemented the "three processing and one compensation" strategy in economic zones such as *Shenzhen* and *Zhuhai*, and has begun to integrate into the world industrialization process as a manufacturing base.

2) *Rapid Development Stage (1992-2002)*

At this stage, China's economy began to enter a stage of rapid development, and the boom of development zones followed. Second generation industrial parks such as *Zhangjiang* High tech and Suzhou Industrial Park were established during this stage, and industrial parks began to spread from the Pearl River Delta to other regions.

3) *Adjustment and Exploration Stage (2003-2015)*

China's accession to the WTO has injected new vitality into the construction of industrial parks. However, in the context of the hot development zone in the previous stage, housing construction has exposed some problems such as unreasonable planning, blind development, and vicious local governments. In 2003, the government began to rectify and adjust industrial parks.

4) *Transformation and upgrading stage (2016 present)*

During the 13th Five Year Plan period, China proposed strategies such as supply side reform, ecological civilization construction, and strategic emerging industries. In this context, industrial parks have also begun to devote themselves to ecological environment protection, and industries have gradually shifted from low-quality energy, chemical, processing and manufacturing industries to high-tech industries.

In this context, with the iteration of industrial functions in China, industrial buildings centered on the secondary industry are gradually being replaced by commercial and office buildings centered on the tertiary industry.

3.3. The problems of industrial buildings

3.3.1. Lack of unified design

Existing productive industrial buildings are mostly built before the 21st century, with main industries including energy and chemical engineering, building materials, and manufacturing. During this period, industrial buildings had different design standards and specifications due to their industry-specific characteristics. In terms of park location, the park is usually located in the suburbs of the city, but as the city expands, this part of the park gradually borders the urban space. At the same time, industrial buildings only meet basic production needs in design, lacking long-term considerations in architectural aesthetics, energy structure, spatial layout, and other aspects. This leads to exaggerated spatial dimensions, inconsistent proportions, or chaotic facade window openings caused by special process requirements in contemporary industrial architecture, which affects the image of the urban interface*(Hanxu,Chen Shizhao,2014)*.

3.3.2. High energy consumption and high carbon emissions

The existing productive industrial buildings are the main force providing important production materials and strategic goods for urban construction during China's rapid urbanization period, characterized by large scale, high energy consumption, and high carbon emissions. At the same time, this type of industrial park is facing the impact of new economy, new industry, and new technology, as well as the dual contradiction of continuing to provide production materials for urban construction, making it difficult to achieve industrialization transformation. Industrial heritage has lost its production function, making it more adept at functional transplantation, spatial optimization, and other aspects of transformation. However, it is difficult to carry out renovation and renovation work on existing productive industrial buildings without affecting their production order.

3.3.3. Serious waste of resources

The waste of resources in industrial buildings is not only reflected in their high energy consumption, but also in their extensive planning strategies, which result in a significant waste of land resources and building space resources. The building facade is an important component of urban space and a significant spatial resource. In the core area of the city, the utilization of facade resources for buildings is relatively sufficient. In contrast, the facade space resources of industrial buildings have not been fully activated and there is still room for development.

4. Research on the Coupling between Photovoltaic Technology and Existing Productive Industrial Buildings

4.1. The Development Process of Photovoltaic Technology

The main basis for photovoltaic new energy technology is the "Photovoltaic Volta" effect. In 1893, French scientist Becquerel discovered the "photovoltaic effect". In 1954, American scientists Chapin and Pearson first developed a solar cell using single crystal silicon as the photovoltaic material*(Hernández-Callejo L, Gallardo-Saavedra S, Alonso-Gómez V,2019)*. The so-called solar cell is a type of optoelectronic semiconductor wafer that directly generates electricity using sunlight*(Yang Qianmiao,Wang Yanting,Wangjiang,2022)*. However, due to the immaturity of the technology, the power generation efficiency of this battery is less than 6%.

The rapid development of the photovoltaic industry began in the mid-20th century and is mainly divided into three stages. The first stage is the crystalline silicon photovoltaic cell stage, characterized by using single crystal silicon and polycrystalline silicon as optoelectronic materials. This type of solar cell has a high energy conversion rate, reaching 26.7%, but it has disadvantages such as high environmental requirements and unstable power. Crystalline silicon solar cells are mainly promoted and applied in centralized energy stations laid on the ground, and there are relatively few application scenarios related to their combination with buildings. The second stage focuses on flexible thin film technology for solar cells. The optoelectronic materials for flexible thin film technology mainly include cadmium telluride, copper indium gallium selenide, and gallium arsenide. Thin film photovoltaic cells have the characteristic of light transmission and are beginning to explore integrated design and application with buildings. But so far, there are still problems such as low energy conversion rates and high costs. The conversion efficiency of thin-film PV modules is 7% to 10%, while the average conversion efficiency of crystalline silicon is 15% *(Qian Bozhang,2008)*. The third stage is diversified material batteries. Such as perovskite photovoltaic cells, dye-sensitized photovoltaic cells, polymer photovoltaic cells, etc. (*Jelle B P , Breivik C , R?Kenes H D,2012*). It has made significant improvements in light sensitivity, plasticity, and conversion rate, but the technology is not yet mature and cannot be widely applied and promoted.

4.2. Study on the Adaptability of Thin Film Photovoltaic Cells to Building Facades

Thin film photovoltaic cells are the second generation of photovoltaic cells after crystalline silicon photovoltaic cells. Unlike the first generation photovoltaic cells, the second generation photovoltaic cell technology involves making conductive media (such as GaAs, CIGS, CdTe) into thin film layers and combining them with glass to form transparent photovoltaic modules. In 2000, researchers such as WuX, Dhere R. G, Aibin D. S developed a solar cell using cadmium telluride (CdTe) as the photovoltaic medium, with an efficiency of 16.4%(*Lee, T. D., & Ebong, A. U. ,2017*). China is in a leading position in the technology of thin-film solar cells. In 2014, the conversion rate of cadmium telluride (CdTe) promoted by the Chinese Academy of Sciences reached 14.4%. In 2021, the energy conversion rate of copper indium gallium selenide (CIGS) solar cells developed by China National Building Materials Group reached 19.64%. In 2023, the energy conversion rate of copper indium gallium selenide (CIGS) solar cells of the same specification by China National Building Materials Group exceeded 20.3%, becoming the first thin-film photovoltaic module to break through 20%. The advancement of thin-film solar cell technology has directly driven the innovation of photovoltaic application scenarios.

4.3. Feasibility of using thin-film photovoltaic cells as building facades

Unlike traditional photovoltaic glass, thin-film photovoltaic cells have characteristics such as transparency and plasticity, and can be applied to various scenarios such as building facades, roofs, and floors.

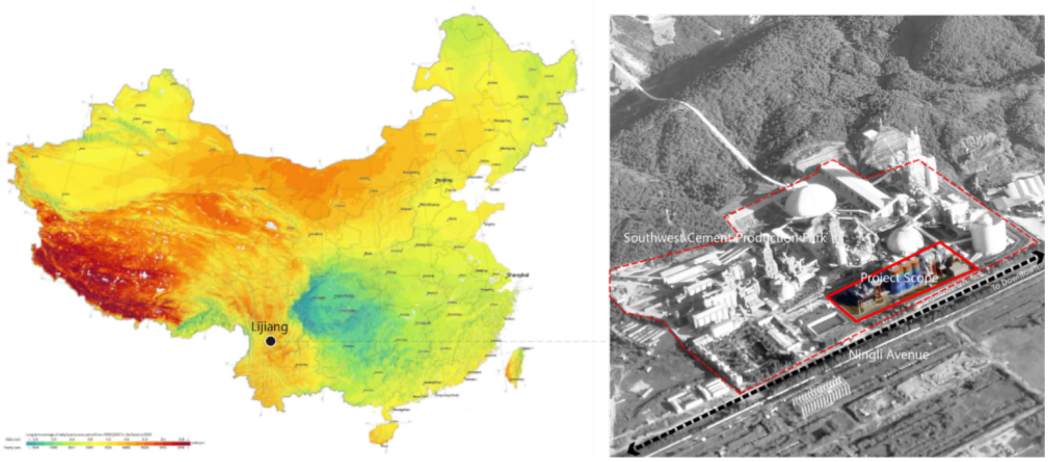

Fig.1. Location of the case

4.3.1. Transparency and Weakness of Thin Film PV Glass

Traditional crystalline silicon photovoltaic cells, due to their opacity, can only be used as carrier spaces on roofs when combined with buildings. The new type of thin-film photovoltaic cells have transparency and can be adjusted according to the needs by adjusting the coating rate to meet different transparency requirements. At the same time, compared with traditional crystalline silicon photovoltaic cells that have higher requirements for the solar azimuth and inclination angle, thin-film photovoltaic glass has better weak light effect and is less restricted by azimuth and inclination angle when deployed. Therefore, this type of photovoltaic glass can be perpendicular to the ground and used as a building curtain wall to ensure good lighting in the internal space of the building.

4.3.2. Structural Strength of Thin Film PV Glass

The structure of thin-film photovoltaic modules has designability. The main manifestation is that the core optoelectronic material components can be combined with glass of different strengths and types, and the combination method can be customized and designed. This also determines to some extent that photovoltaic modules have the characteristics of windproof, waterproof, sound insulation, and impact resistance, making the structural strength of the modules adaptable to the relevant requirements of different building facades. Meanwhile, the weak light effect of thin-film photovoltaic modules enables them to generate electricity continuously even without an optimal tilt angle.

4.3.3. High plasticity of thin-film PV glass

Photovoltaic glass using cadmium telluride, copper indium gallium selenide, and gallium arsenide as dielectrics is an organic combination of new optoelectronic materials and glass carriers, also known as thin-film photovoltaic. As a new photovoltaic technology, thin-film photovoltaic modules have stronger plasticity than crystalline silicon photovoltaic modules. Firstly, it has the functionality of generating electricity through traditional photovoltaic modules; Secondly, it has the translucent characteristics of glass, and the transparency can be customized according to needs, which can be widely used in scenarios such as building curtain walls, roofs, and building ceilings; Finally, its specifications can be customized according to different scenario requirements.

5. Case Study

5.1. Background

The research was carried out in the 5000t/d intelligent production line park of the Old Town of Lijiang Southwest Cement Co., Ltd. The project is located in Lijiang City, Yunnan Province, adjacent to the tourist artery, the Lining Highway. The project involves renovating the facades of cement packaging areas, cement storage areas, and cement grinding areas along the highway. The usable building facade area of the park exceeds 30000 square meters, and the first phase includes a renovated facade area of approximately 12400 square meters. The goal of the project renovation is to: (1) convert the abundant local solar energy resources into electricity and consume it nearby to reduce the demand for traditional energy in the park; (2) Using new photovoltaic glass to beautify building facades and

Fig.2. Status of building facade

improve the working environment of building production.

5.2. Analysis of Existing Problems and Strategies

Yunnan is a region with abundant solar energy resources in China, and belongs to the "I" category in the distribution of solar energy resources in China. The total annual solar radiation in the research area is 1719kWh/m^2, and the full load illumination time is about 6 hours. Photovoltaic power generation is the optimal choice. The overall orientation of the park is towards the south. According to research, there are several problems with the architecture in the park, including: 1)Lack of unified design for building facades, inconsistent materials and colors for facades, making it difficult to form an overall architectural style, especially for buildings along *Ningli* Road where the facade space is severely fragmented and fragmented; 2)The building structure is complex, with various structures such as steel-concrete, brick concrete, and color steel. There are many external ancillary facilities on the building facade, which affect the beauty of the building, such as ladders, ventilation pipes, etc. In response to the above issues, the project has adopted the following design strategies:

1) *Weaving and repairing space, beautifying the facade*

Differentiated design is carried out for different facade conditions of buildings. The facade of the cement storage area is complete and has a good display surface, designed with colored photovoltaic glass. The cement batching area, grinding area, and packaging area have complex building facades and fragmented spaces. Black cadmium telluride glass material is used to reorganize the building facades based on the principle of integrity.

2) *Innovate technology and improve efficiency.*

In order to fully utilize solar energy resources, the project space mainly consists of building facades, and traditional crystalline silicon photovoltaic cells have high requirements for solar azimuth and inclination angles. Therefore, the project selects a new type of cadmium telluride power glass as the material, fully utilizing the high plasticity and weak light effect of cadmium telluride power glass, and adopts a design method of overall veneer tiling without setting inclination angles.

5.3. System Design

5.3.1. Section Division

According to the different functions, facade features, and building heights of the buildings in the park, the project will divide the renovated building complex into three different areas and implement differentiated design. Among them, Area A is a cement packaging workshop with a building height of 29.5 meters, Area B is a cement batching workshop and grinding workshop with a building height of

Table1. The Planning of CdTe PV Glasses

Section	Building Function	Facade Area（m2）	PV Module(Blocks)	Installed Cpacity（kWp)
A	Packaging area	1755	704	158
B	Storage area	4223	2012	391
C,D	Ingredient and grinding area	2120	793	180
Total		5978	2716	549

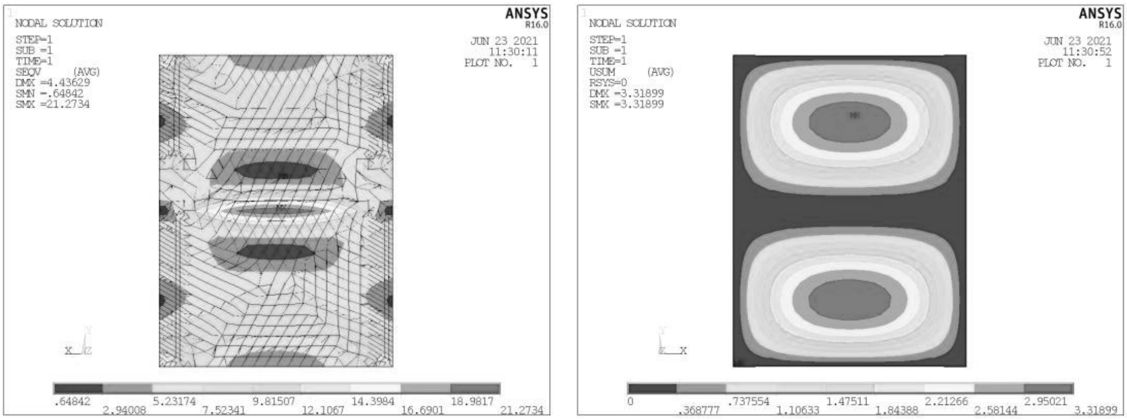

Fig. 3. The performance test parameters of CdTe PV Glasses

about 29 meters, and Area AB is a flat facade with a relatively low building height, designed as a black photovoltaic glass curtain wall. Area C is a cement storage area with a building height of 50 meters and good visibility, using colored photovoltaic glass curtain walls. Meanwhile, according to the composition of different facades, the photovoltaic modules and installed capacity also vary, as shown in the table 1.

5.3.2. Material selection and performance testing

Cadmium telluride (CdTe) photovoltaic glass is a new type of photovoltaic module that uses cadmium telluride as the photovoltaic medium. It is a new type of thin-film photovoltaic cell that can be used for building facades and is considered a green, recyclable, and power generating multifunctional building material that can replace traditional building materials such as bricks and curtain walls(*Ma Liyun,Fu Ganhua,Guanmin,2022*). Cadmium telluride photovoltaic glass has the following characteristics: (1) strong power generation capacity and high energy conversion efficiency; (2) Low temperature coefficient and good weak light power generation performance; (3) The installation angle has minimal impact and thermal spot effect, making it suitable for application in distributed, component-based, and integrated green energy buildings.

Unlike traditional BAPV technology, when BIPV photovoltaic modules are installed and applied on building facades, in addition to their own power generation performance, they also need to meet the requirements of building thermal performance and safety performance. The photovoltaic modules installed on the building facade need to meet the requirements of thermal insulation, sound insulation, load and fire prevention of the building. The cadmium telluride power generation glass panel used in the project currently has no current standard specification reference. In order to ensure the strength and stiffness requirements of the panel, a structural analysis of the panel will be conducted separately based on the corresponding product testing report. For panels that do not meet the requirements, reinforcement measures will be added to the back of the panel to improve its strength and stiffness. A policy simulation was conducted on photovoltaic glass modules using ANSYS-R16.0 software, with a maximum stress of 21.7N/mm2 on the surface material and a maximum displacement of 3.3mm. The components meet the requirements of the Technical Code for Glass Curtain Wall Engineering (JGJ102-2003) in terms of strength and stiffness(Fig.3).

5.3.3. Design of Photovoltaic Facade Structure System

The project adopts standard cadmium telluride glass components with dimensions of 1600mm*1200mm, with 2-3cm reserved for deformation joints, and 4-5 components are electrically connected in series. At the same time, in order to meet the requirements of curved building facades, the installation method of curtain walls adopts a "horizontally hidden and vertically visible" keel skeleton. Embedding cadmium telluride power generation glass components in the glass curtain wall structure not only ensures that the appearance of the curtain wall is not affected, but also protects the normal operation of cadmium telluride power generation glass components from external environmental factors such as wind loads and rainwater. In this structure, the glass panels can float in all directions up, down, left, and right with seismic waves, meeting the requirements for displacement, and the waterproof and anti air infiltration methods are simple and reliable. The front end of the frame is equipped with a heat-insulating strip made of

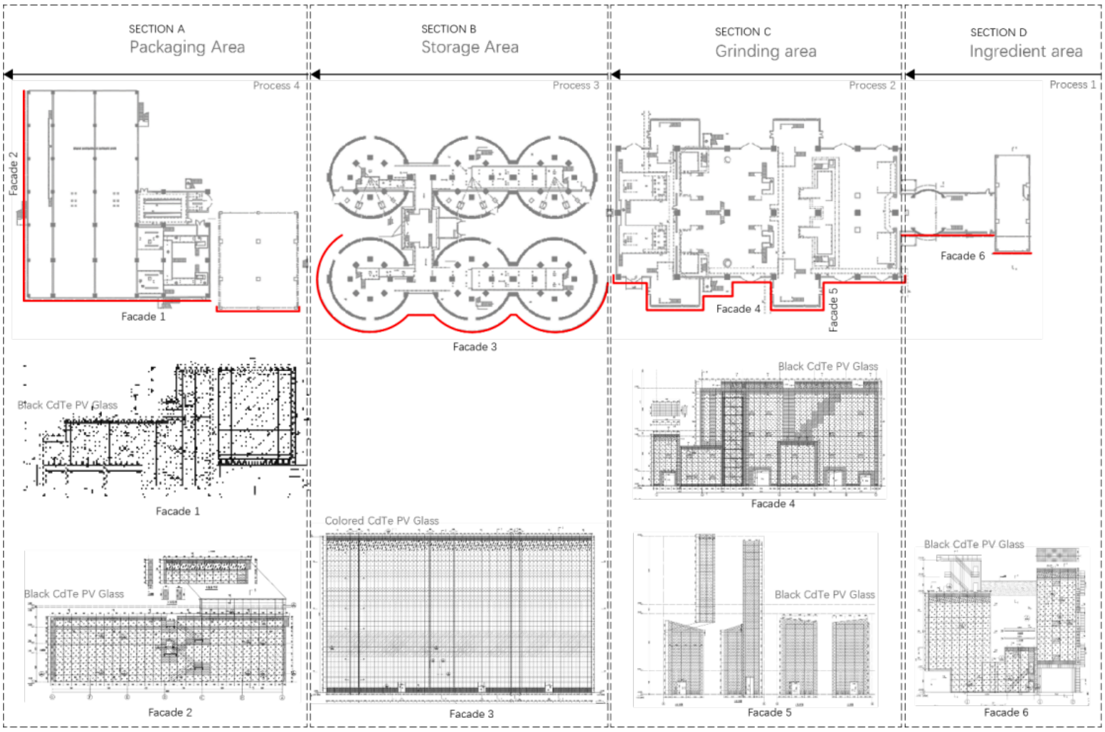

Fig. 4. Photovoltaic Facade Structure System

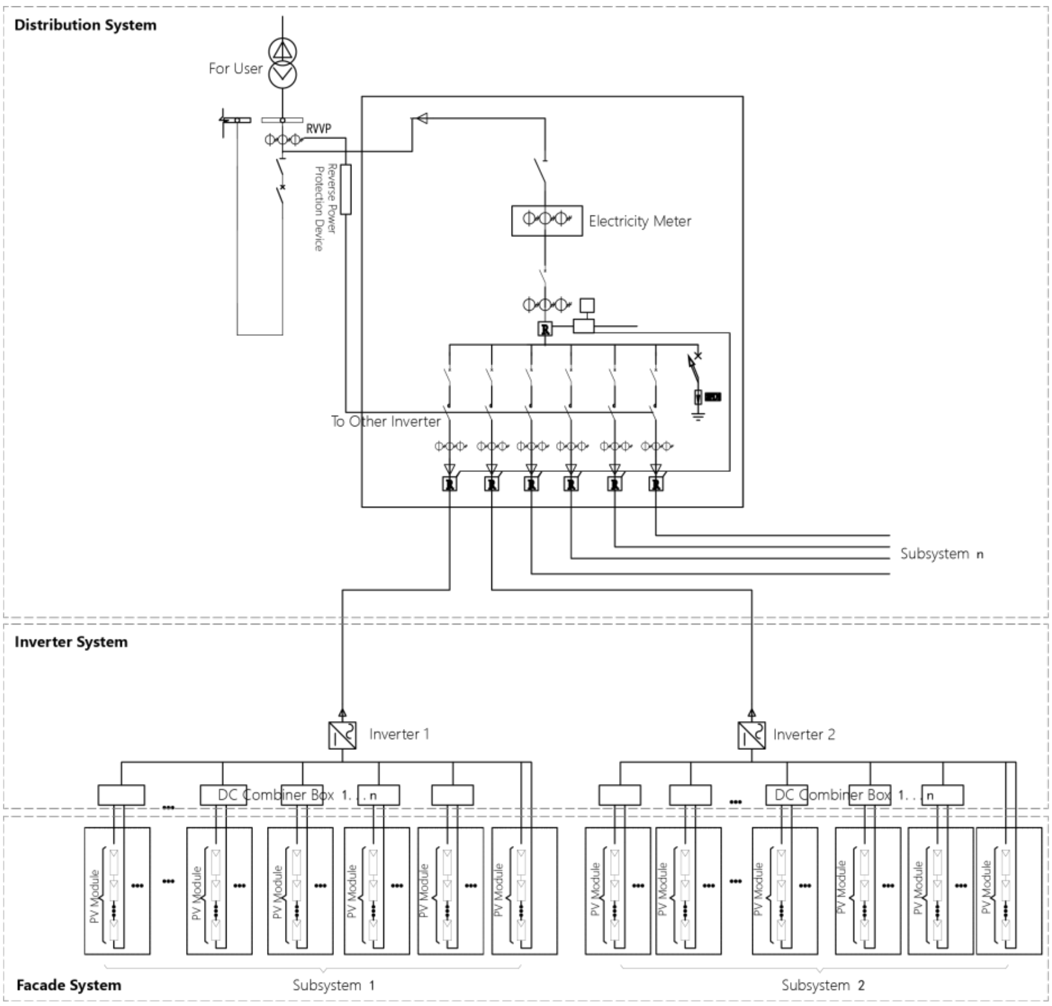

Fig. 5. Electrical system design

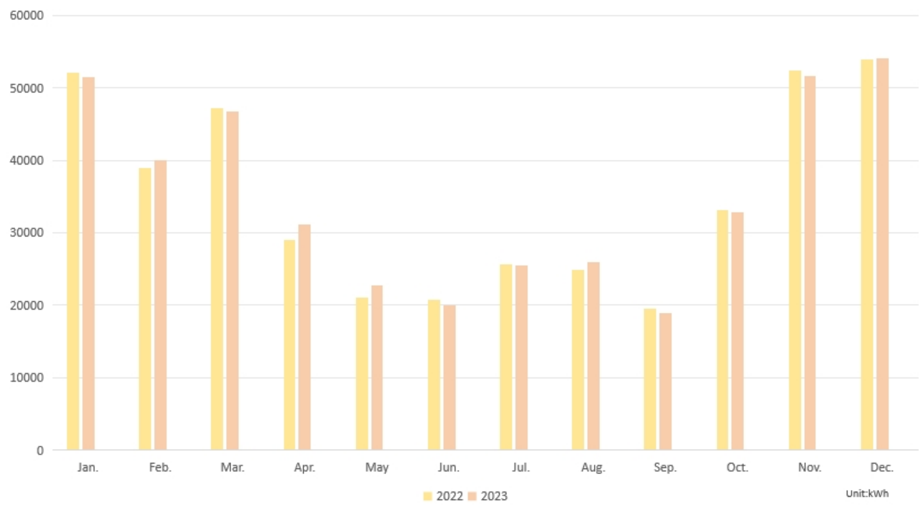

Fig. 6. Power Generation Statistical Table of Photovoltaic Facade

non-conductive material, which can better block the conduction of indoor and outdoor cold and warm air, prevent the occurrence of indoor condensation water in cold seasons, meet the environmental protection concept of energy conservation and emission reduction, and save energy indoors.(Fig.4)

5.3.4. Electrical system design

The building photovoltaic system can be divided into independent photovoltaic power generation system and grid connected photovoltaic power generation system according to the connection mode with the public power grid. The project adopts a low-voltage grid connection strategy, and the electrical system architecture diagram is shown in Figure *. Due to the attachment relationship between photovoltaic modules and curtain walls, photovoltaic modules are greatly influenced by the building facade shape, and there are local differences in the power generation efficiency of photovoltaic modules in various parts. Therefore, in order to ensure the overall power generation efficiency of the project, the project design fully considers the different lighting conditions and adopts a zoning distribution method. On the one hand, the project has made differentiated adjustments in the combination of photovoltaic arrays, incorporating photovoltaic glass of the same power into a unified array; On the other hand, the project will connect photovoltaic arrays of different colors, specifications, and orientations to different inverters, or different MPPTs of the same inverter.

6. Research Results and Discussion

6.1. Result

The total installed capacity of the project is 726KW, with 4 low-voltage grid connection points, 36 string inverters, 208 DC combiner boxes, and 2 AC combiner boxes. The average annual power generation of the project is about 678400 kWh. According to local industrial electricity prices, it is expected to save 346000 yuan in electricity and energy costs annually. At the same time, using solar energy for power generation can save 206.9 tons of standard coal, reduce carbon dioxide emissions by 552.2 tons, sulfur dioxide emissions by 4.2 tons, and nitrogen oxide emissions by 1.4 tons.

Although there are currently no relevant technical specifications for cadmium telluride power glass, the special support design also ensures the stability of project operation. The structural stability of the photovoltaic glass makes it capable of withstanding wind, water, earthquake, and impact in building structural strength. Therefore, its feasibility in participating in the integrated design of photovoltaic buildings has been evaluated.

The cement storage area is designed with colored cadmium telluride power glass due to its high building height and large display area. Adhering to the design concept of "Colorful Yunnan", seven different colored components are arranged to highlight the regional cultural characteristics. In addition, the aesthetic characteristics of texture, color, and modularity of the photovoltaic glass can promote the secondary utilization of building facade space resources while ensuring the overall style of

Fig. 7. Status Photo of the Industrial Building Facade after Renovation

the building, even in urban spaces where large areas of idle land resources cannot be provided.

The research results can be applied to other similar industrial building facades, such as building structure maintenance, energy-saving curtain walls, and roofs. Not only can it improve residents' stereotypical impression of traditional industrial buildings as dirty, messy, and poor, but it can also fully utilize the facade space resources and abundant solar energy resources of the buildings. The produced electricity can not only be self absorbed, optimizing the energy structure of the park to reduce dependence on traditional energy, but also the excess electricity can be connected to the internet and fed back to other industrial energy sources.

6.2. Discussion

6.2.1. BIPV application scenarios lag behind

The application efficiency of photovoltaic buildings is still affected by installation costs and natural climate. Improving the service life of photovoltaic modules, reducing the installation cost of photovoltaic systems, and enhancing the power generation efficiency of photovoltaic buildings in winter are still key considerations for photovoltaic building integration.

6.2.2. Aesthetics and functionality cannot be fully integrated yet

Due to the efficiency of photovoltaic module power generation, the material size and aesthetics cannot be fully integrated at present. In order to achieve better power generation efficiency, different types of thin-film photovoltaic modules have fixed sizes. Taking CdTe thin film components as an example, a top domestic material research and development institution can only provide three sizes: 1200mm*1600mm, 1200mm*800mm, 1200mm*400mm. The rest of the customized sizes will have an impact on the product's energy absorption. Although customization of the size, transmittance, shape, and combination form of photovoltaic modules is allowed in research and development, their high modification costs and unstable energy performance make their application not widespread. That is to say, if power generation efficiency is prioritized, existing specifications of boards need to be designed. If aesthetics are prioritized, existing specifications of boards need to be customized, which will affect power generation efficiency.

6.2.3. The power generation efficiency of photovoltaic modules is still not stable enough

The installation angle of cadmium telluride power generation glass components is arranged on the curved facade of the building. Therefore, in winter, the distributed power station has a high solar altitude angle, which leads to the direct laying of light that is relatively parallel to the facade components and cannot form a strong incident angle, resulting in a lower energy conversion rate of solar energy. Therefore, in terms of power generation, there is a trend of the highest in winter and the lowest in summer.

7. Conclusion

This research demonstrates the significant potential of integrating photovoltaic technology with industrial building facades, offering a sustainable approach to energy structure optimization and architectural aesthetics. By employing cadmium telluride (CdTe) photovoltaic glass in the renovation of industrial buildings, particularly in production-oriented settings, the study validates the feasibility of utilizing thin-film photovoltaic technology to meet both energy and structural demands. The practical application in Lijiang's Southwest Cement Co. highlights how innovative design strategies can transform industrial architecture, improving energy efficiency and aesthetic value while reducing environmental impacts.

However, challenges remain in the widespread application of Building Integrated Photovoltaics (BIPV), particularly in balancing aesthetics with functionality, optimizing power generation efficiency, and managing installation costs. Future research should focus on advancing material customization technologies, developing standardized guidelines for photovoltaic building integration, and exploring cost-effective methods to increase the adaptability of photovoltaic systems in various architectural contexts.

The findings of this study provide a valuable reference for future projects aiming to modernize industrial buildings while contributing to carbon neutrality goals. This approach can be scaled to similar industrial contexts, fostering sustainable development and redefining the role of industrial architecture in urban spaces.

Reference

1. Deng Yuanyuan, Li Han, Yang Nan,&Zhu Yiwen (2023). Research on the transformation of existing industrial relics based on BIM Building Economics, 44 (S01), 339-343
2. Gao Changzheng, Yan Fang,&Long Wenyan (2017). Exploration of Industrial Heritage Transformation Model Based on "Symbiosis Theory" - Taking Luoyang Bearing Factory as an Example Urban Development Research, 24 (3), 7
3. Han Xu,&Chen Shizhao (2014). Aesthetic treatment of details in industrial building facade design - expression of authenticity and modernity Industrial building (S1), 4
4. Hernandez-Callejo, L. , Gallardo-Saavedra, S. , & Alonso-Gomez, V. . (2019). A review of photovoltaic systems: design, operation and maintenance. Solar Energy, 188(AUG.), 426-440.
5. Huang Lei Research on the Evolution of Historical Industrial Space Form from the Perspective of Urban Sociology (Doctoral dissertation, Hunan University)
6. Huang Xinyu,&Chen Wen (2022). The current status and development prospects of building integrated photovoltaics (BIPV) applications Journal of Civil Engineering and Management (003), 039
7. Jelle, B. P. , Breivik, C. , & R?Kenes, H. D. . (2012). Building integrated photovoltaic products: a state-of-the-art review and future research opportunities. Solar Energy Materials and Solar Cells, 100(5), 69-96.
8. Lee, T. D., & Ebong, A. U. (2017). A review of thin film solar cell technologies and challenges. Renewable and Sustainable Energy Reviews, 70, 1286-1297.
9. Li Jian, Chen Qingchang,&Ma Xiyin (2021). Exploration of Urban Design Strategies for the Yangpu Shipyard Area in Shanghai under the Concept of "Fiber Block" Planner, 37 (13), 7
10. Liu Boying, Hu Rongrui, Li Rong, Wu Fangbo, Hu Jianxin,&Vera (2018). Research on non industrial transformation technology of existing industrial buildings Industrial Architecture, 48 (11), 8
11. Liu Na, Huang Jingnan,&Zhou Jun (2023). Exploration of Planning Strategies for Industrial Heritage Protection in Urban Central Areas: Taking the Old Site of Huaxin Cement Plant in Huangshi City, Hubei Province as an Example Planner, 39 (2), 117-124
12. Ma Liyun, Fu Ganhua, Guan Min, Yu Tao, Xie Liusha,&Qian Xuejun, etc (2022). Research and industrialization progress of cadmium telluride thin film solar cells Journal of Ceramics, 50 (8), 8
13. Qian Bozhang (2008). Overview of the Development of Thin Film Photovoltaics Chemical New Materials, 36 (010), 54-55
14. Ren Binbin, Wang Jingshuang, Xiao Shaoying, Li Jianhua,&Li Haoxuan (2023). Research on the vitality of industrial heritage in the central urban area of Tianjin based on multi-source data Modern Urban Studies, 38 (5), 59-67
15. Wang Hongwei, Zhu Xueting,&Yin Chenxi (2022). Quantitative Economics, Technical Economics Research, 39 (7), 23
16. Wang Yi and Chen Jing (2008). Exploration and Practice of Industrial Park Planning under the Concept of Sustainable Development Industrial architecture, 38 (12), 4
17. Wang Yunke (2021). A Preliminary Study on the Development History of Modern Industrial Architecture Research in China (Doctoral dissertation, Nanjing University)
18. Yang Chunhong,&Pu Yunyun (2023). Research on modular design of prefabricated industrial buildings based on low-carbon concept Building Technology, 54 (14), 1707-1710
19. Yang Qianmiao, Wang Yanting,&Wang Jiang (2022). Feasibility Study on the Application of Solar Photovoltaic Technology in Traditional Buildings Building Energy Efficiency (in Chinese and English), 50 (7), 5
20. Zhang Jian, Xie Yingming,&Yang Yuanhao (2017). Economic and Environmental Benefit Analysis of Photovoltaic Wall BAPV System Building Energy Efficiency, 45 (3), 6
21. Zhang Jie, Li Minhua,&Jie Yang (2023). Technological Innovation in Industrial Heritage Protection and Utilization Leading Urban Renewal - Jingdezhen Modern Porcelain Heritage Protection and Renewal Series Practice Journal of Architecture (4), 6-11

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Address：
1-53-13, Nishigahara
Kita City, Tokyo
114-0024
Japan

Tel: +81 (0)80-8515-9423

E-mail: editorialoffice.jgtss@press.jandoo.ac

Offical website: https://press.jandoo.ac/journals/jgtss

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