International Journal of Innovative Computing, Information and Control
Volume **20**, Number **6**, December **2024**

ICIC International ©2024 ISSN 1349-4198
pp. 1765–1773

OPTIMIZATION OF ZHENGZHOU RAIL TRANSIT STATION AREAS BY SPATIAL MODIFICATION UNDER TOD THEORY

Jialin Hou and Guimin Ma*

School of Architecture and Urban Planning
Henan University of Urban Construction
Longxiang Avenue, Xincheng District, Pingdingshan 467036, P. R. China
20172111@huuc.edu.cn; *Corresponding author: maguimin@huuc.edu.cn

Received November 2023; revised April 2024

Abstract. *This article briefly introduces the transit-oriented development (TOD) theory and constructs a mathematical model for optimizing the spatial layout of land use in areas surrounding rail transit stations. The particle swarm optimization (PSO) algorithm is then employed to solve the mathematical model. In order to enhance the efficiency of the PSO algorithm, the crossover and mutation operations of the genetic algorithm were introduced. An empirical analysis was conducted using the undeveloped area within a 500-meter radius around Yanzhuang Subway Station in Zhengzhou City, Henan Province. The results indicated that the improved PSO algorithm iterated 400 times before converging to stability and converged faster than the traditional PSO algorithm (600 times). Both the traditional PSO algorithm-optimized and the improved PSO algorithm-optimized land planning schemes showed improvements compared to the initial scheme, among which the improved PSO algorithm-based scheme being more consistent with TOD mode characteristics and had a higher fitness value. In the improved PSO scheme, the objective function value for transportation passenger volume was* 4.9×10^{10}*, the objective function value for environmental quality was* 3.2×10^{7}*, and the objective function value for economic benefits was* 3.1×10^{8}*. In contrast, in the traditional PSO scheme, the objective function values were* 4.3×10^{10}*,* 2.8×10^{7}*, and* 2.5×10^{8}*, respectively.*

Keywords: Transit-oriented development, Rail transit, Transit station area, Spatial layout of land use

1. **Introduction.** With the development of urbanization, there are many challenges, among which traffic congestion and shortage of land resources are one of the most prominent problems [1]. Therefore, it is necessary to do a good job of planning in the process of urbanization development to ensure the sustainability and efficiency of urbanization development. Transit-oriented development (TOD) theory is capable of alleviating traffic congestion. This theory takes public transportation as the guidance to plan the land space [2]. Rail transit station areas play an important role in TOD theory, and it is also a core area in urban planning and development, which can effectively alleviate traffic congestion [3]. Xu and Yan [4] proposed a comprehensive model based on TOD theory to concurrently optimize land use and transportation in China's urban rail transit coverage areas under the background of new urbanization. They studied Jianzhou New Town to verify the effectiveness of the model. Motieyan and Mesgari [5] proposed a three-step method based on TOD and evaluated the performance of the model through a case. Li et al. [6] employed fuzzy analytic hierarchy process for establishing the evaluation index of TOD model, applied it to Shanghai, China, and proposed an optimization plan based on the evaluation outcomes. The aforementioned studies all utilized the TOD theory to

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DOI: 10.24507/ijicic.20.06.1765

optimize land use plans, and this paper similarly employs particle swarm optimization (PSO) under the guidance of TOD theory to optimize land layout schemes. This paper constructed an optimization model that can measure the quality of land layout schemes using TOD theory. Additionally, to enhance the optimization performance of the PSO algorithm, a genetic algorithm was also introduced. In this paper, a mathematical model for the spatial layout optimization of rail transit station areas was constructed. Then, the PSO algorithm was used to solve the mathematical model. To enhance the solving efficiency of the PSO algorithm, the crossover and mutation operations of the genetic algorithm were introduced. Then, a case study was carried out on the area to be developed within a radius of 500 m around Yanzhuang Subway Station in Zhengzhou City, Henan Province. This article aims to provide a reasonable division of the undeveloped areas within the areas surrounding rail transit stations. The key contribution lies in utilizing the PSO algorithm to optimize the division scheme for development areas and introducing the genetic algorithm's crossover and mutation operations to enhance the PSO algorithm's optimization performance. This study offers effective references for optimizing layout plans of rail transit station areas.

2. Optimization of Land Use Space for Rail Transit Station Areas Based on TOD.

2.1. TOD theory.

TOD is a mode of urban development oriented to public transportation. Its core is to use public transportation stations [7], especially subway, light rail, bus and other traffic stations as the core of urban development, and establish an urban circle that can make full use of transportation facilities to ease land use contradictions [8]. The core concept of TOD model is people-oriented, focusing on residents' experience and ecological value [9].

Combined with TOD theory, the evaluation hierarchical structure of spatial layout of land use in areas surrounding rail transit station is shown in Figure 1. The evaluation can be carried out from three aspects: the traffic passenger flow, the regional environmental quality, and the regional economic benefit. The traffic passenger flow reflects the transportation convenience of the rail transit station area. The regional environmental quality reflects the environmental quality of the station area, which indirectly indicates the sustainability and living environment for nearby residents [10]. The regional economic benefit reflects the economic benefits that can be brought by the architectural planning in the station area. Transportation convenience, environmental quality and economic benefits can facilitate the sustainable growth of rail transit station areas. According to the

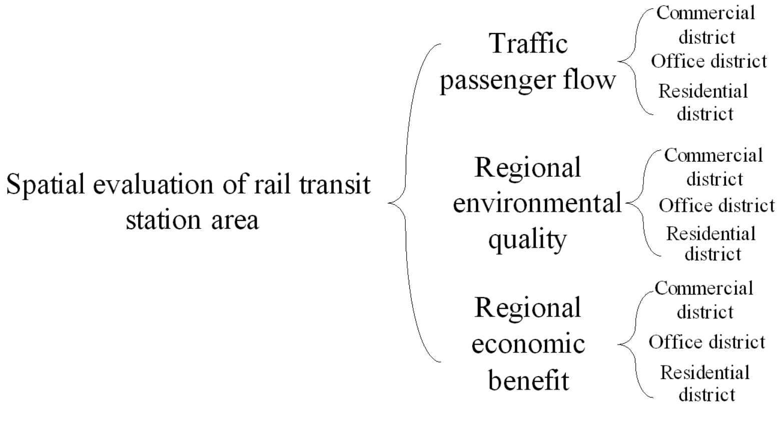

Figure 1. Hierarchical model of land use space evaluation for rail transit station areas based on TOD

above evaluation hierarchical structure, an evaluation model can be constructed to measure the quality of land use spatial layout. However, certain assumptions need to be made before constructing the model [11]. ① The optimization of land use spatial layout made in this study is to adjust the distribution of different types of land use, and the type, quantity, and area of each land use have been determined. ② Residents who use the rail transit station start from this station. ③ The decision variable of the evaluation model is the distance between the regional center of the plot and the center of the station. The above assumptions have simplified the reality to facilitate subsequent calculations, so the optimization results obtained may deviate from the actual situation. This article aims to verify the applicability of the PSO algorithm in land layout optimization. Designing more realistic and detailed land allocation plans is a future research direction.

2.2. **Optimization of land spatial layout based on improved PSO algorithm.**

The improved PSO algorithm based on the genetic algorithm is adopted of the spatial layout of land use in areas surrounding rail transit stations. The process is as follows.

① After setting the population size, the population particles are randomly created, and the coordinates of each particle in the search space are a spatial layout plan of land use. The quantity of axes in this space is determined by the amount of plots that require optimization, and the value on each axis is the distance between the corresponding plot and the center of the station.

② After decoding the population particles, the distance between the corresponding plot and the station is substituted as a decision variable into the following model formula to calculate the fitness value of each particle:

$$\begin{cases} y_1 = \sum_i \left(s_i^b \cdot m_i^b \cdot t_i^b \cdot k_i^b \cdot f\left(x_i^b\right)\right) + \sum_j \left(s_j^o \cdot m_j^o \cdot t_j^o \cdot k_j^o \cdot f\left(x_j^o\right)\right) \\ \qquad + \sum_k \left(s_k^u \cdot m_k^u \cdot t_k^u \cdot k_k^u \cdot f(x_k^u)\right) \\ y_2 = \dfrac{\sum_c s_c^g}{\sum_i \left(s_i^b \cdot m_i^b \cdot x_i^b \cdot l_i^b\right) + \sum_j \left(s_j^o \cdot m_j^o \cdot x_j^o \cdot l_j^o\right) + \sum_k \left(s_k^u \cdot m_k^u \cdot x_k^u \cdot l_k^u\right)} \\ y_3 = \sum_i \left(s_i^b \cdot m_i^b \cdot a_i^b \cdot x_i^b \cdot avg_i^b\right) + \sum_j \left(s_j^o \cdot m_j^o \cdot a_j^o \cdot x_j^o \cdot avg_j^o\right) \\ \qquad + \sum_k \left(s_k^u \cdot m_k^u \cdot a_k^u \cdot x_k^u \cdot avg_k^u\right) \end{cases}, \tag{1}$$

where y_1, y_2, and y_3 are traffic passenger flow, regional environmental quality, and regional economic benefits, s_i^b, s_j^o, s_k^u, and s_c^g are the area of plots with serial numbers i, j, k, and c corresponding to commercial district b, office district o, residential district u, and public district g, m_i^b, m_j^o, and m_k^u are the plot ratios of lands with corresponding serial numbers [12], t_i^b, t_j^o, and t_k^u are the average quantities of daily trips in the corresponding plot, k_i^b, k_j^o, and k_k^u are the proportion of people in the corresponding plot who choose rail transit, x_i^b, x_j^o, and x_k^u are the decision variables of the corresponding plot, $f(\,)$ is the mapping relationship between decision variables and travel times, l_i^b, l_j^o, and l_k^u are the walking impedance coefficients in the corresponding plot, a_i^b, a_j^o, and a_k^u are the aggregation degrees of the corresponding plot, and avg_i^b, avg_j^o, and avg_k^u are the relative land increments of the corresponding plot [13].

③ Whether the algorithm reaches the termination condition is determined. If so, the optimal particle is output from the population, and it is decoded to get the planning scheme of the land space. If the termination condition is not reached, the algorithm enters the next step. Generally, the termination condition is that the iteration reaches the set threshold, or the fitness value of the population particle converges and stabilizes [14].

④ The PSO iterative formula is used to update the position and velocity of the population particles [15], and the formula is

$$\begin{cases} V_{i+1} = V_i + a_1 \cdot c_1 \cdot (pbest_i - P_i) + a_2 \cdot c_2 \cdot (gbest_i - P_i) \\ P_{i+1} = P_i + V_{i+1} \end{cases}, \tag{2}$$

where P_i and V_i are the position and velocity of particle i, $pbest_i$ and $gbest_i$ are the individual historical best position and the current global best position, a_1 and a_2 are learning factors, c_1 and c_2 are random numbers, which is evenly distributed between 0 and 1.

⑤ In the improved PSO algorithm, the PSO iterative formula is employed for the updating of particle velocity and position, and the genetic operation is carried out on the particles. The crossover operation involves the random selection of two particles for the exchange of values along a common axis, and the possibility of the exchange of the values on the axis depends on the crossover probability. Mutation operation is that the value on the coordinate axis in a particle changes randomly under the constraints, and the possibility of random change depends on the mutation probability. After updating the population by genetic operation, go back to step ②.

3. Case Study.

3.1. Analysis object.

This paper took the rail transit station area of Zhengzhou City, Henan Province as an example. By September 2023, there were eight rail transit routes. Each route had a different number of stations. The environment of each station was different. It would be too heavy to analyze all stations, so this paper selected one of them for analysis. This site was chosen because it has a moderate amount of traffic, neither so little as to be unrepresentative nor so much as to be difficult to count, and secondly, because there is a sufficiently large area around the site to be developed. Figure 2 shows the general situation of the area to be developed near the Yanzhuang Subway Station of Zhengzhou rail transit. Yanzhuang Subway Station is the intermediate station of Zhengzhou Metro Line 1, which is located in Jinshui District of Zhengzhou City. Its overall structure is an underground three-storey island station with a total of five entrances and exits.

3.2. Parameter setting.

The relevant parameters of plots to be planned within a radius of 500 m around Yanzhuang Subway Station are presented in Table 1. In addition, the average daily travel rate and walking impedance coefficient of the plots with different uses are as follows. The average daily travel rate of the plots in the commercial district was 1.2 people/m^2, and the walking impedance coefficient was 1.35. The average daily travel rate of the office district was 0.35 people/m^2, and the walking impedance coefficient was 1.03. The average daily travel rate of the residential district was 0.12 people/m^2, and the walking impedance coefficient was 0.95. The average daily travel rate of different regional plots was obtained through local statistics, while the walking impedance coefficient was set based on experience combined with relevant literature.

The related parameters of the improved PSO algorithm obtained by orthogonal tests are presented in Table 2.

The traditional PSO algorithm optimized the spatial planning scheme of land use, and the new scheme was compared with the scheme optimized by the improved algorithm. It shared the same parameters as the improved PSO algorithm except for no crossover and mutation probability.

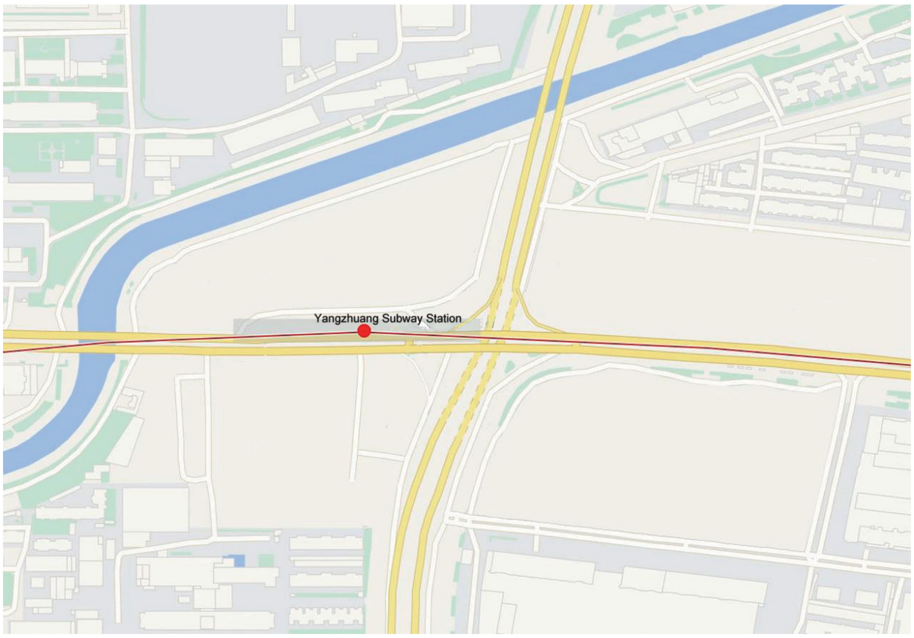

Figure 2. General situation of the area to be developed in Yanzhuang Subway Station, Zhengzhou City, Henan Province

Table 1. Relevant parameters of plots to be planned

Plot number	Land use type	Area/m	Plot ratio	Relative land increment yuan/m	Degree of land agglomeration
# 1	Office district	12154	2.0	698.69	68796
# 2	Residential district	14586	2.5	875.36	75896
# 3	Office district	12026	2.0	1114.21	64754
# 4	Office district	11897	2.5	658.68	35897
# 5	Residential district	36987	1.5	235.21	48796
# 6	Residential district	10241	1.5	768.35	75487
# 7	Residential district	13254	4.0	875.68	65481
# 8	Commercial district	13869	3.5	1120.11	28975
# 9	Residential district	21368	3.5	657.36	68796
# 10	Commercial district	19852	1.5	235.47	75896
# 11	Commercial district	21697	2.5	578.67	64754
# 12	Office district	21357	2.0	897.47	35897
# 13	Commercial district	23146	2.0	114.53	62845
# 14	Commercial district	19856	2.5	896.36	56874
# 15	Office district	24157	1.5	2145.87	46893
# 16	Office district	12588	1.5	1876.54	52147
# 17	Residential district	10214	3.0	368.47	48796
# 18	Commercial district	9568	3.0	568.58	75487
# 19	Commercial district	9897	3.5	789.68	65481
# 20	Residential district	35896	2.5	879.63	41052
# 21	Office district	9987	2.0	987.69	71542
# 22	Office district	10122	2.5	3574.84	32547
# 23	Office district	9988	2.0	2589.64	41052

Table 2. Parameter settings of the improved PSO algorithm

Parameter	Setting	Parameter	Setting
Particle population	30	Inertia weight	0.5
Learning factor	2	Maximum number of iterations	1000
Crossover probability	0.6	Mutation probability	0.1

3.3. **Experimental results.** Figure 3 presents the convergence curves of two PSO algorithms in optimizing the spatial planning scheme of land use. Since the model used to measure the quality of the land use planning scheme in this paper is a multi-objective optimization model, and the units and orders of magnitude of the three objective functions were different, the calculation results of the objective function were normalized in order to observe the convergence curve changes of the two algorithms in the optimization process in the same figure. The method of min-max normalization was adopted, which involves subtracting the minimum value from the original data and then dividing it by the difference between the maximum and minimum values. It can be seen from Figure 3 that the objective functions of the two optimization algorithms rose as the number of iterations increased and reached stability after a certain number of iterations. The traditional PSO algorithm needed about 600 iterations before each objective function converged to stability, and the improved algorithm required about 400 iterations before each objective function converged to stability. Moreover, it can be intuitively seen that the objective function obtained by the improved algorithm was higher than that of the traditional algorithm after the two algorithms converged and stabilized, respectively.

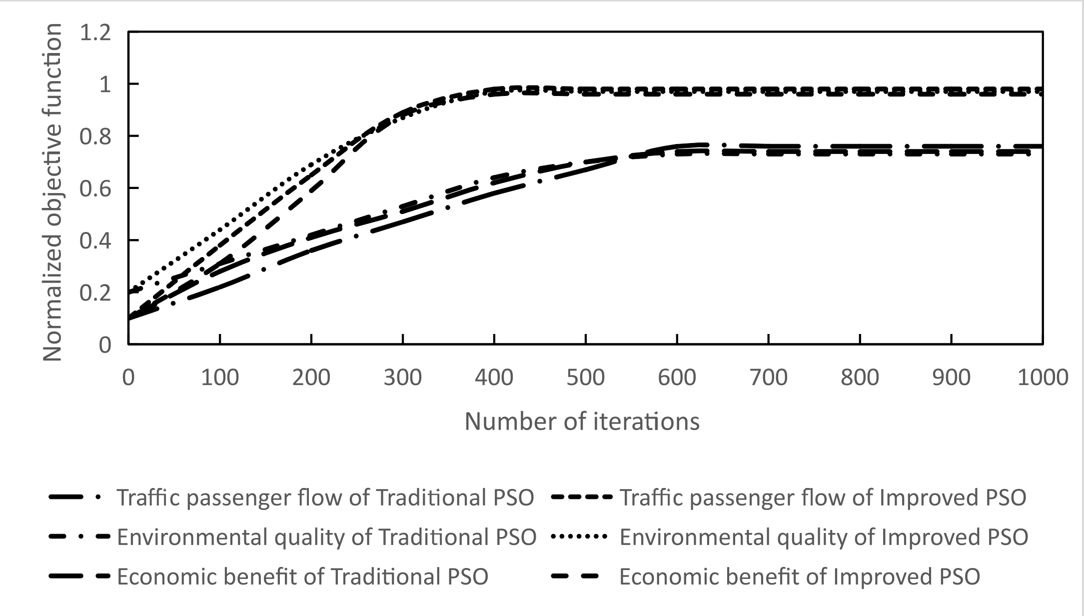

Figure 3. Convergence curves of two PSO algorithms

For multi-objective optimization problems, there is more than one suitable optimization scheme. Limited by space, this paper only shows the original planning scheme and part of the scheme optimized by two algorithms, as shown in Figure 4. In the original planning scheme, the plots with different uses were relatively scattered in distribution. After the optimization by the traditional PSO algorithm, the plots showed a clustering, but there was still a certain gap with the principles described by TOD theory. After the optimization by the improved algorithm, the plots with different uses not only showed aggregation,

Original planning scheme Traditional PSO algorithm-based planning scheme

Improved PSO algorithm-based planning scheme

FIGURE 4. The original planning scheme and part of the optimized schemes

TABLE 3. The average distance of each type of plot and the objective function value under different planning schemes

Types of plot	Average distance of the original scheme	Average distance of the traditional PSO algorithm-optimized scheme	Average distance of the improved PSO algorithm-optimized scheme
Commercial district	298	281	272
Office district	297	267	233
Residential district	305	234	187
Objective function value of traffic passenger flow	3.3×10^{10}	4.3×10^{10}	4.9×10^{10}
Objective function value of environmental quality	2.6×10^{7}	2.8×10^{7}	3.2×10^{7}
Objective function value of economic benefit	2.2×10^{8}	2.5×10^{8}	3.1×10^{8}

but also radiated outward from the Yanzhuang Subway Station in a sequence, including commercial district, office district, and residential district.

Table 3 shows the average distance between each type of plot and the station and the objective function value of the original scheme and the planning scheme given by two algorithms. The Pareto solution set is shown in Figure 5. Compared with the original scheme, the objective function values of the two schemes optimized by the algorithm were improved, and the objective function value of the improved PSO algorithm-optimized

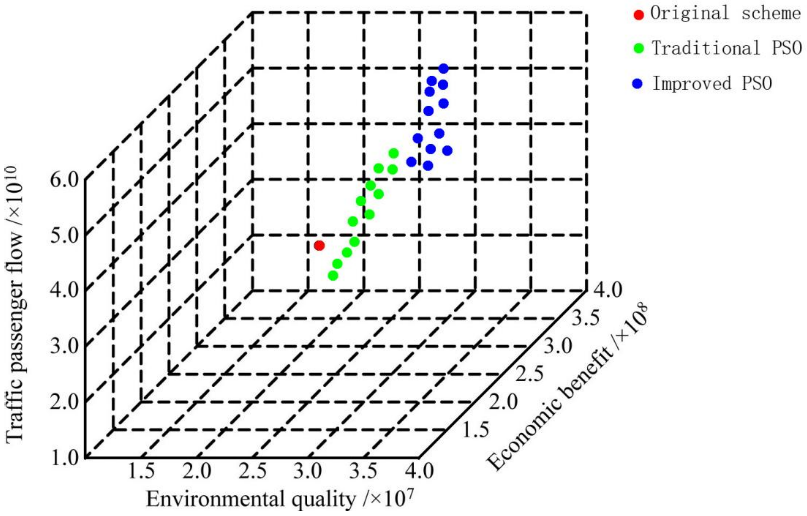

FIGURE 5. The Pareto solution of two optimization algorithms

scheme was improved more. From the point of view of the average distance of each type of plot and the station, it was reduced in the scheme optimized by the algorithm, and the average distance of the improved PSO algorithm-optimized scheme was reduced the most, which was in line with the plot planning distribution in Figure 4.

4. **Conclusion.** In this paper, a mathematical model of land use spatial layout optimization of rail transit station was constructed. Then, the PSO algorithm was employed to solve the mathematical model. To enhance the solving efficiency of the PSO algorithm, the crossover and mutation operations of the genetic algorithm were introduced. Then, a case study was performed on the area to be developed within a radius of 500 m around Yanzhuang Subway Station in Zhengzhou City, Henan Province. The key findings are summarized below. 1) The traditional PSO algorithm needed about 600 iterations before each objective function converged to stability, and the improved PSO algorithm needed about 400 iterations before each objective function converged to stability. 2) Compared with the original planning scheme, different types of parcels showed a certain degree of clustering after optimization. The clustering of different plots in the improved PSO algorithm-optimized planning scheme was higher, and the distribution was more in line with the TOD theory. 3) Compared with the original planning, the average distance between each type of plot and the station was reduced after optimization, and the objective function value was increased. The average distance between each type of plot and the station in the improved PSO algorithm-optimized scheme was the smallest, and the objective function value was the largest.

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Author Biography

Jialin Hou, from 2008 to 2013, studied in Henan University of Urban Construction and received her Bachelor's degree in 2013. From 2014 to 2017, she studied in Beijing University of Civil Engineering and Architecture and received her Master's degree in 2017. She is a lecturer and works at Henan University of Urban Construction. She is interested in transportation architecture design, station area planning, and residential architecture and environmental design.

Guimin Ma, from 2001 to 2006, studied in Wuhan University and received his Bachelor's degree in 2006. From 2006 to 2009, he worked in Henan University of Urban Construction. From 2009 to 2012, he studied in Huazhong University of Science and Technology and received his Master's degree in 2012. From 2014 to 2022, he studied in Tianjin University and received his Doctor's degree in 2022. He is an associate professor and works at Henan University of Urban Construction. He is interested in transportation architecture design, station area planning, and digital architectural design.