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TOD MODE: STUDY ON LAND PLANNING AND LAND USE OPTIMIZATION FOR URBAN RAIL TRANSIT STATION AREA

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Abstract:

The rational planning of land around rail transit stations in cities can effectively improve the convenience of transportation and economic development of cities. This paper briefly introduced the transit-oriented development (TOD) mode of urban planning. We constructed a hierarchical structure for evaluating the quality of land planning of urban rail transit stations through the analytic hierarchy process (AHP) method. The structure started from three large aspects, i.e., traffic volume, regional environmental quality, and regional economic efficiency, and every large aspect was divided into three small aspects. Then, an optimization model was established for land planning of rail transit stations. The land planning scheme was optimized by a genetic algorithm (GA). To enhance the optimization performance of the GA, it was improved by coevolution, i.e., plural populations iterated independently, and every population replaced the poor chromosomes in the other populations with its excellent chromosomes in the previous process. Finally, the Jinzhonghe street station in Hebei District, Tianjin city, was taken as a subject for analysis. The results suggested that the improved GA obtained a set of non-inferior Pareto solutions when solving a multi-objective optimization problem. The distribution of solutions in the set also indicated that any two objectives among traffic volume, environmental quality, and economic efficiency was improved at the cost of the remaining objectives. The land planning schemes optimized by the particle swarm optimization (PSO) algorithm, the traditional GA, and the improved GA, respectively, were superior than the initial scheme, and the optimized scheme of the improved GA was more in line with the characteristics of the TOD mode than the traditional one and the PSO algorithm, and the fitness value was also higher. In conclusion, the GA can be used to optimize the planning design of land in rail transit areas under the TOD mode, and the optimization performance of the GA can be improved by means of coevolution.

Keywords: *transit-oriented development, rail transit, land planning, genetic algorithm*

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1. Introduction

In the context of the global advocacy of developing intensive, green, organic, three-dimensional future cities, China has proposed the basic urban transportation policy-public transport first (Furlan and Al-Mohannadi, 2020) and opened a total of 277 operating lines, which is 9067 km long. The integrated development of rail and urban renewal offers new opportunities and modes for sustainable urban development.

The infrastructure development and services are improved while enhancing the city's traditional accessibility. Reasonable land replacement is promoted through economic leverage (Shishir and Mathur, 2019) to attract multiple capital injections, reduce resistance to renewal, and shorten the renewal construction cycle, bringing continuous vitality to the area through the gathering of people at a later stage. In the process of developing the land around the rail transit stations, scientific analysis is needed according to the actual local situation, and more appropriate land planning should be designed to give full play to the role of transportation rail stations (Niu et al., 2021).

This paper briefly introduced the TOD mode of urban planning. The authors constructed a hierarchical structure for evaluating the quality of land planning of urban rail transit stations through the analytic hierarchy process (AHP) method to establish an optimization model for land planning of rail transit stations. The land planning scheme was optimized by a genetic algorithm (GA). To enhance the optimization performance of the GA, it was improved by coevolution. Finally, the Jinzhonghe street station in Hebei District, Tianjin was taken as a subject for analysis.

The innovation of this paper is to use the GA to optimize the land planning scheme and to introduce coevolution in the traditional GA to improve its performance. The contribution of this paper is to plan lands based on the optimization performance of the GA, which provides an effective reference for the optimization of land planning.

2. Literature review

Some studies related to how to better plan the land near urban rail stations are as follows. Nguyen et al. (2020) used the linear regression method to assess the impact of accessibility to urban services and transportation on real estate prices in Hanoi, thus facilitating the effective development of urban rail transit under the transit-oriented development (TOD) mode. Liu et al. (2020) illustrated the corridor-TOD (C-TOD) framework and optimization tools using Wuhan Metro Line 2 in China as an example and verified that the C-TOD concept and tools could help practitioners and policy makers to expand TOD applications by improving land use planning and decision making.Li et al. (2019) used fuzzy hierarchical analysis to construct evaluation indicators for TOD, applied them to Shanghai, China, and proposed optimization scheme based on the evaluation results. Taki et al. (2017) reviewed various studies related to the integration of land use and transportation with TOD and concluded that practicing and integrating TOD through land use and transportation was an alternative solution to achieve overall planning goals and solve urban problems such as urban congestion, travel time, and automobile dependence. Zhou et al. (2021) proposed an algorithm that combined a structural equation model with a neural network algorithm for evaluating urban planning solutions, applied it to the planning of Lantau Island, Hong Kong. The final computational simulation results showed that the employment/population goals envisioned for the new city were achievable by increasing the accessibility of transportation infrastructure supply.

Nigro et al. (2019) applied the TOD planning mode to a case study in the Campania region of southern Italy and pointed out a possible method for assessing the integration of land use and public transportation while considering the quality of the transportation network. Agyemang et al. (2020) explored the benefits of implementing the TOD mode in Accra, including reducing motorization and congestion and increasing walkability and other forms of non-motorized transport, and proposed some recommendations based on the analysis.Shishir (2019) presented a framework for funding the Delhi Metro using the land value capture tool and found that many factors related to land use planning and policy limited the size of land value capture revenues. In the aforementioned literature, different researchers have approached the optimization of land planning near rail stations from different perspectives, but all of them have followed the TOD mode in the optimization process, so that the planned land use scheme can facilitate the travel of urban residents.

3. TOD mode

Although private cars can provide convenience for residents in progressively larger cities, not all families can afford expensive cars, and moreover, the increase in private cars will lead to an increase in carbon emissions (Teklemariam and Shen, 2020). Therefore, in order to improve the convenience of urban travel and minimize carbon emissions, the scale of public transportation facilities has been increased. The construction of public transportation facilities will occupy the construction area of land, which means that it will affect the surrounding land planning. If the land planning around a public transportation station does not consider the influence on the station, it will neither properly divide the land area nor give full play to the role of the station (Barbé and Frascaria-Lacoste, 2021).

The TOD mode is a transportation planning mode. It can improve the transportation capacity and environmental carrying capacity of a city through rational planning of transportation routes. The TOD mode is also an urban planning mode that considers the full utilization of urban land when planning urban buildings (Ermini et al., 2021) and facilities. Compared with other urban planning modes, the TOD mode also gives priority to the influence of traffic routes in a city to coordinate urban land planning and the development of urban transportation (Kong et al., 2019).

The TOD mode means rationally develop and utilize land within a certain range (generally a distance of about 10 minutes on foot) centered on a transportation station to construct a commerce, office, and residence integrated functional area a good transport environment. The basic features of the TOD mode include: (1) the use of transport means is considered in the planning of land; (2) a slow traffic environment suitable for walking and bicycling is built in the planning; (3) the planning layout around the transportation station is compact and diversified; (4) the transportation station can effectively link the surrounding living, commercial, and office areas (Zhou and Wang, 2020).

4. Optimization algorithm combined with the TOD mode for land planning

4.1. Hierarchical structure of land planning evaluation based on the TOD mode

First, the hierarchical structure for evaluating the quality of land planning is divided using the AHP method; then, the objective function of land planning optimization based on the TOD mode is constructed according to the divided hierarchical structure, i.e. the optimization model. Figure 1 shows the hierarchical structure for evaluating the quality of land planning. In this paper, the land scale is evaluated from three major aspects, namely, passenger capacity, environmental quality, and economic benefits, and every major aspect is divided into three minor aspects, namely, commercial area, office area, and residential area (Bao et al., 2019).

According to the hierarchical structure of land planning evaluation in the AHP method, the objective function for optimizing the land planning scheme in the TOD mode is the sum of rail traffic capacity, environmental quality of the station area, and economic benefits of the station area in the design scheme. However, in the actual design, it is not easy to determine the weight of every objective when integrating them, and the three objectives will interfere with each other during optimization. Simply speaking, the planning design that enhances the objective of one aspect will not enhance the objectives of the other two aspects (Ma et al., 2021). Therefore, instead of using the evaluation of the three objectives after integration as the objective function of optimization, the three objectives are separated, i.e., the land planning design is transformed into a multi-objective optimization problem to search for a design scheme that can compromise the three objectives.

4.2. Land planning optimization using the improved GA

The land planning design optimization problem is transformed into a multi-objective optimization problem in the previous section. Before constructing the optimization objective function model for this multi-objective optimization problem, some assumptions need to be made, because there are many factors that can affect the planning and design, and considering all of them will complicate the operation (Lung-Amam et al., 2019). The following assumptions are proposed. Firstly, the number of land types and the land area to be planned around the station have been determined, and the optimization subject is the distribution of different types of land around the station. Secondly, the people who takes this rail transit around the station start from the station. Thirdly, in the process of optimizing the land planning scheme, the planned land on the map plane is approximated as the origin, and the distance between the origin of the planned land and the station is determined by the distance between the center of the planned land and the station.

Objective functions:

$$\begin{cases} Z_1 = \sum_i (S_i^b \cdot m_i^b \cdot T_i^b \cdot K_i^b \cdot f(x_i^b)) + \sum_j (S_j^o \cdot m_j^o \cdot T_j^o \cdot K_j^o \cdot f(x_j^o)) + \sum_k (S_k^u \cdot m_k^u \cdot T_k^u \cdot K_k^u \cdot f(x_k^u)) \\ Z_2 = \dfrac{\sum_c S_c^g}{\sum_i (S_i^b \cdot m_i^b \cdot x_i^b \cdot l_i^b) + \sum_j (S_j^o \cdot m_j^o \cdot x_j^o \cdot l_j^o) + \sum_k (S_k^u \cdot m_k^u \cdot x_k^u \cdot l_k^u)} \\ Z_3 = \sum_i (S_i^b \cdot m_i^b \cdot A_i^b \cdot x_i^b \cdot avg_i^b) + \sum_j (S_j^o \cdot m_j^o \cdot A_j^o \cdot x_j^o \cdot avg_j^o) + \sum_k (S_k^u \cdot m_k^u \cdot A_k^u \cdot x_k^u \cdot avg_k^u) \end{cases} \quad (1)$$

Constraints:

$$\begin{cases} x \in [0, x^*] \\ x_i^b < x_j^o < x_k^u \\ x_i^b \in (0, x_i^{b*}) \\ x_k^u \in (x_k^{u*}, x^*) \end{cases} \quad (2)$$

where Z_1, Z_2, and Z_3 are the number of rail passengers, the environmental quality of the site area, and the economic benefits of the site area, respectively, b, o, and u are commercial, office, and residential areas, respectively, i, j, and k are the plot number of the corresponding land use types, S_i^b, S_j^o, S_k^u, and S_c^g are the land area of the commercial, office, residential, and public areas, m_i^b, m_j^o, and m_k^u are the plot ratio of the commercial, office and residential areas (Suryani et al., 2020), T_i^b, T_j^o, and T_k^u are the average number of daily trips of the commercial, office, and residential areas, and K_i^b, K_j^o, and K_k^u are the proportion of people choosing rail transit in the commercial, office and residential areas, x_i^b, x_j^o, and x_k^u are the distance between the commercial, office and residential areas and the station, which is the decision variable to be planned, $f(\cdot)$is the mapping relationship of the decision variable to the number of trips, l_i^b, l_j^o, and l_k^u are the walking impedance coefficient of the commercial, office and residential areas (Duncan et al., 2021), A_i^b, A_j^o, and A_k^u are the aggregation degree of the commercial, office, and residential areas, avg_i^b, avg_j^o, and avg_k^u are the relative land appreciation of the commercial, office, and residential areas, x^* is the optimal range of the station area, which is obtained by the pedestrian walking distance obtained through the field survey, and x_i^{b*} and x_k^{u*} are the optimal theoretical distance of the commercial and residential areas.

In the land planning optimization model constructed in the previous section for the traffic station area, the plots to be planned are approximated as points, and their distance from the center of the site is used as the decision variable. After that, the GA (Huang et al., 2020) is used to optimize the decision variables in the optimization model.

When the traditional GA optimizes the decision variables, it first generates chromosomes under the constraints according to the planned plots to be optimized. Every chromosome represents a land planning scheme. The genetic locus on the chromosome represents the distance of a plot.

The number of chromosome gene fragments depends on the number of plots to be optimized. After generating the chromosome population, the particles are decoded to get the land layout schemes, and the optimization model is used to calculate the fitness values of the three objective functions. Whether the iteration needs to continue is determined according to the fitness value. If not, the planning scheme is output, and if it continues, the fitness values are recalculated after the genetic operation of the population and judged again until the iteration is terminated.

In order to improve the optimization performance of the GA, coevolution (Dirgahayani et al., 2020) is introduced. The improved GA uses three populations to find the optimum at the same time and uses the relatively good chromosomes to replace the bad ones in the iterative process. The process is shown in Figure 2. The specific steps are described below.

1. The length of chromosomes is set according to the number and type of plots to be optimized.

Three initial populations are randomly generated under the constraints of the optimization model. The three initial populations have the same size but different chromosomes.

2. After decoding the chromosomes in the population and obtaining the land planning layout, the rail traffic passenger volume, station area environmental quality, and station area economic benefits of the planning scheme represented by the chromosomes are calculated using equation (1) (Na et al., 2021).
3. Whether the iteration needs to be terminated is determined. If it does, the result after iteration is output and decoded into a land planning scheme; if it does not, it goes to the next step. The conditions to terminate the iteration include the population fitness value converging to stable or the number of iterations reaching the preset number.
4. The three populations uses some of their optimal chromosomes to replace the poor chromosomes in the other populations. To be specific, the top 30% of excellent chromosomes in population 1 replaces the bottom 30% of poor chromosomes in population 2. The same operation is performed between populations 2 and 3 and between populations 3 and 1.
5. The crossover operation in this paper is a single-point crossover (Poerbo, 2020), which means that two chromosomes are selected according to the crossover probability and one of the same gene positions is exchanged; the mutation operation is that a single chromosome causes the value on the gene position to change randomly within the constraint according to the mutation probability. Then return to step 2.

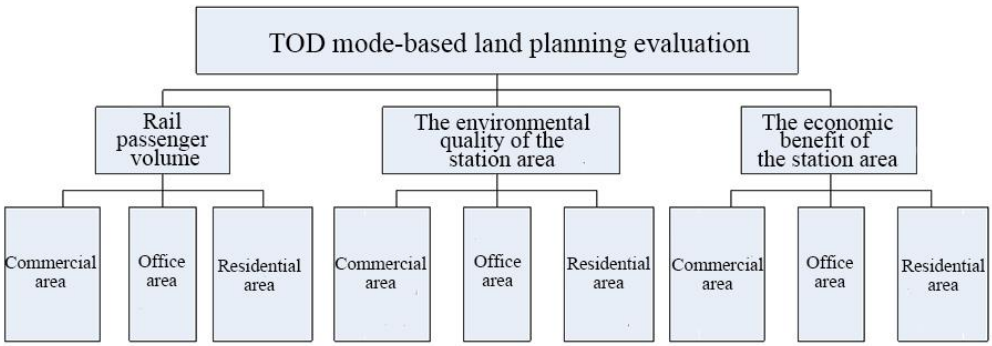


Fig. 1. The hierarchical structure of evaluating the quality of land planning for urban rail transit stations

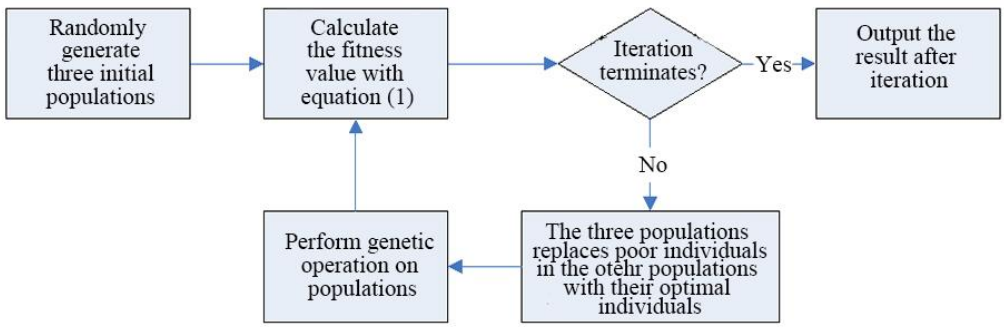


Fig. 2. Places of incidents involving pedestrians and motor vehicles in the Silesian Voivodeship in 2016-2021

5. Case analysis

5.1. Case overview

An urban rail transit station, Jinzhonghe street station in Hebei District, Tianjin, was used as an example for analysis. The initial land planning scheme for the Jinzhonghe street station within a radius of 600 m from the center of the station is shown in Figure 3. When planning the undeveloped land within 600 m of the Jinzhonghe street station, 20 plots were divided for the construction of commercial, office, and residential areas. #1, #5, #6, #7, #9, #15, and #20 plots were residential areas, #2, #3, #4, #8, #11, #12, and #17 plots were office areas, and 10, #13, #14, #16, #18, and #19 plots were commercial areas.

5.2. Parameter setting

When the improved GA was used to optimize the land planning scheme near the rail transit station, the distance between the plot and the station was used as the decision variable, which was the parameter to be optimized. The other relevant parameters in the objective function in the optimization process are shown in Tables 1 and 2 after the field survey.

Fig. 3. The initial land planning scheme for Jinzhonghe street station

Table 1 Type, area, plot ratio, relative land appreciation, and aggregation degree of different plots

Plot no.	Use	Area/m^2	Plot ratio	Relative land appreciation Yuan/m^2	Land aggregation degree
#1	Residential area	25684	2.0	768.35	39874
#2	Office area	13568	2.5	875.68	28975
#3	Office area	11247	2.0	1120.11	68796
#4	Office area	20159	2.5	657.36	75896
#5	Residential area	26578	1.5	-235.47	64754
#6	Residential area	24163	1.5	578.67	35897
#7	Residential area	11258	4.0	897.47	48796
#8	Office area	20579	3.5	-114.53	75487
#9	Residential area	24156	3.5	1203.14	65481
#10	Commercial area	26587	1.5	879.63	41052
#11	Office area	19897	2.5	987.69	71542
#12	Office area	10247	2.0	3574.84	32547
#13	Commercial area	9876	2.0	2589.64	34789
#14	Commercial area	10698	2.5	758.98	47586
#15	Residential areas	8741	1.5	896.36	35478
#16	Commercial area	9987	1.5	2145.87	45879
#17	Office area	18978	3.0	1876.54	62845
#18	Commercial area	25413	3.0	-368.47	56874
#19	Commercial area	22369	3.5	568.58	46893
#20	Residential areas	20547	2.5	789.68	52147

Table 2. Average daily trip rate and walking impedance coefficient for different plot types

Plot type	Commercial area	Office area	Residential area
Average daily trip rate n/m^2	1.0	0.15	0.16
Walking impedance coefficient	1.25	1.18	1.17

The relevant parameters of the improved GA were obtained through orthogonal experiments, as follows. The size of all three independent populations was set as 50; the crossover probability was 0.8; the mutation probability was 0.2; the selection ratio was 0.2; the maximum number of iterations was 300.
In addition, to further verify the optimization effect of the improved GA, the traditional GA was also used to optimize the land planning scheme as a comparison. The population size of the traditional GA was 150, and the rest of the parameters were consistent with the improved GA. In addition to the traditional GA, the improved GA was also compared with the PSO algorithm. In the PSO algorithm, the population size was set as 150, the two learning factors were both set as 1.5, the maximum number of iterations was set as 1500, and the inertia weight was 0.8.

5.3. Experimental results

The improved GA was used to optimize the planning scheme for the land around the rail transit station. There were three optimization objectives in the process of optimizing the land planning scheme, so it was a multi-objective optimization problem. In the process of solving the multi-objective optimization problem, there was antagonisms among the three optimization objectives, i.e., the decision variables could not be adjusted to improve the three optimization objectives at the same time, so in the iteration process of the improved GA, even if the population fitness value converged, the final solution was not a single optimal solution, but a set of non-inferior solutions. In simple words, there would be multiple suitable land planning optimization schemes. Figure 4 shows the Pareto solution after convergence of the improved GA. The blue dots represent the initial land planning schemes, and the red dots represent the set of Pareto solutions after convergence. It was observed from Figure 4 that the polymerization extent of the solution set after convergence was relatively high and significantly far from the initial solution, and the three optimization objectives of every solution in the Pareto solution set were better than those of the initial solution. In addition, the distribution of the solutions in the Pareto solution set also showed that there was a mutual constraint among the three optimization objectives, and the solutions on the edge of the Pareto solution set all had two improved optimization objectives but one reduced optimization objective.

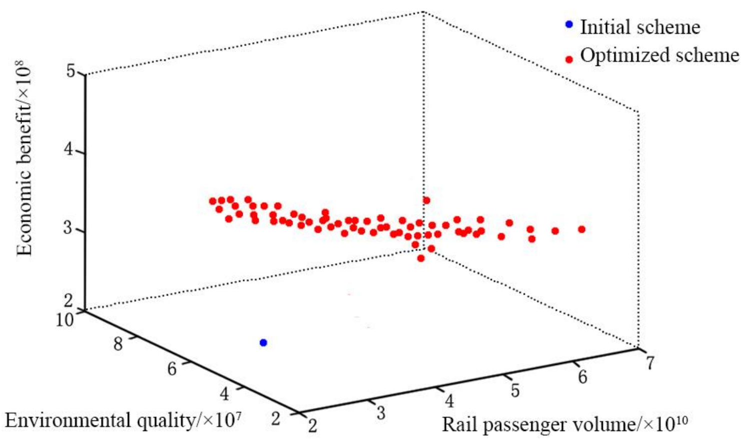
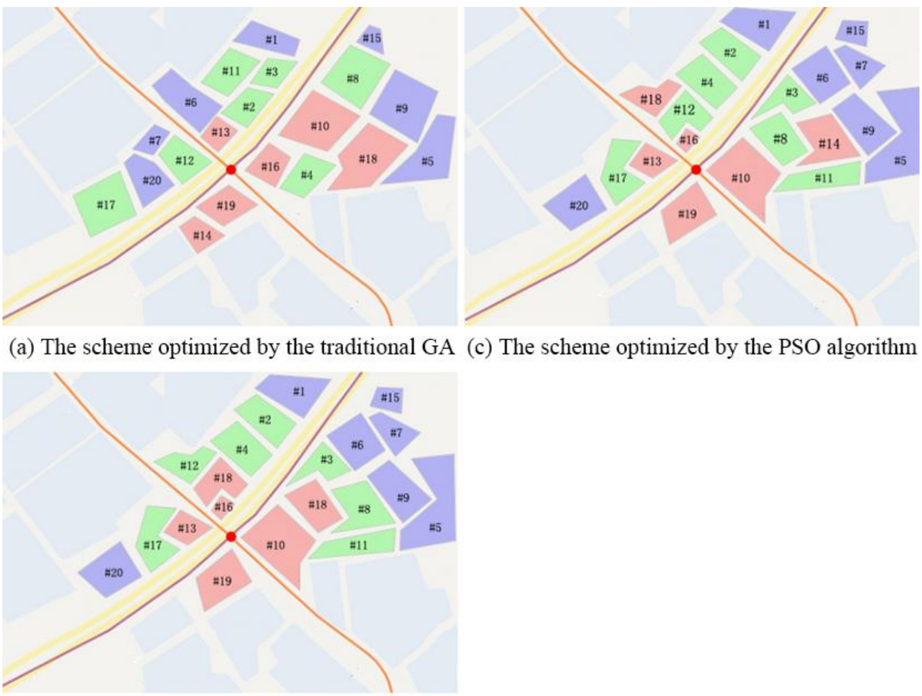


Fig. 4. Pareto solutions under the improved GA after convergence

A multi-objective optimization problem will almost never have a unique optimal solution in the optimization process but usually has a solution set composed of a complex number of non-inferior solutions. Due to the limitation of space, this paper only shows some of the optimization solutions of land planning in three algorithms, as shown in Figure 5. In Figure 5, (a) is the land planning scheme obtained by the traditional GA, (b) is the land planning scheme obtained by the improved GA, and (c) is the land planning scheme optimized by the PSO algorithm. Comparing the three schemes with the initial land planning scheme, it was found that under the optimization of the three algorithms, the commercial area was closer to the station, followed by the office area, and the residential area was at the periphery. It was said that the land planning scheme of the three optimization algorithms followed the characteristics of the TOD mode. Comparing the optimization schemes between the three algorithms, it was visually seen that the optimized scheme obtained by the improved GA had a more concentrated commercial area, and the distribution of commercial, office, and residential areas was closer to the concentric rings. Table 3 shows the distances between different plots and the station in the initial land planning scheme, the distances between different plots and stations in the land planning schemes of the three algorithms shown in Figure 5, and the objective function values of the four land planning schemes. The decision variables of the four planning schemes in Table 3 are shown on the map in Figures 3 and 5. The land planning schemes optimized by the three algorithms fit the characteristics of the TOD mode more closely than the original scheme, and the land planning scheme under the improved GA fit the concentric rings that conform to the TOD characteristics more closely in terms of layout. The objective function values of the four planning schemes in Table 3 showed that the planning scheme obtained by the improved GA had a large fitness value, which further verified that the improved GA could plan the land layout near the rail transit station in a way that was more suitable for the TOD mode.



(a) The scheme optimized by the traditional GA (c) The scheme optimized by the PSO algorithm

(b) The scheme optimized by the improved GA

Fig. 5. Partial of the land planning optimization schemes under three algorithms

Table 3 The initial land planning scheme and partial of the land planning schemes under the three algorithms

Plot no.	Use	Decision variable of the initial scheme	Decision variable of the traditional GA	Decision variable of the improved GA	Decision variable of the PSO algorithm
#1	Residential area	532	503	576	577
#2	Office area	495	256	426	420
#3	Office area	451	468	403	404
#4	Office area	512	264	384	386
#5	Residential area	543	512	526	524
#6	Residential area	321	298	486	489
#7	Residential area	342	289	531	533
#8	Office area	333	487	298	246
#9	Residential area	338	496	336	336
#10	Commercial area	297	258	135	137
#11	Office area	198	301	248	251
#12	Office area	201	154	243	205
#13	Commercial area	254	124	128	136
#14	Commercial area	250	214	246	298
#15	Residential area	263	541	582	579
#16	Commercial area	258	125	120	126
#17	Office area	200	305	236	235
#18	Commercial area	298	376	205	253
#19	Commercial area	208	124	137	130
#20	Residential area	489	206	326	331
Rail passenger volume		4.3×10^{10}	5.3×10^{10}	5.9×10^{10}	5.5×10^{10}
The environmental quality of the station area		3.6×10^{7}	3.8×10^{7}	4.2×10^{7}	4.0×10^{7}
The economic benefit of the station area		2.2×10^{8}	2.5×10^{8}	3.1×10^{8}	2.8×10^{8}

6. Conclusion

This paper briefly introduced the TOD mode of urban planning, constructed a hierarchical structure for evaluating the quality of land planning of urban rail transit stations through the AHP method, and established an optimization model for land planning of rail transit stations. The land planning scheme was optimized by the GA. To enhance the optimization performance of the GA, it was optimized by coevolution. Finally, the Jinzhonghe street station in Hebei District, Tianjin was taken as a subject for analysis.The following results were obtained. The Pareto solution set obtained after optimization by the improved GA was significantly superior to the initial solution, but there were mutual constraints among the three optimization objectives, two of which were improved at the cost of reducing the remaining one objective. The layouts optimized by the PSO algorithm, traditional GA, and improved GA fit the characteristics of the TOD mode more closely than the initial scheme, while the layout optimized by the improved GA and PSO algorithm fit the TOD mode better than the traditional GA. The improved GA-optimized solution had the highest fitness value, followed by the PSO algorithm and traditional GA, and the initial solution had the lowest value.

The limitation of this paper is that the objective function established in the optimization of land planning scheme by the GA was simplified to a certain extent, so the optimized land planning scheme was still different from the practical one. Therefore, the future research direction is to establish a more realistic land planning model to make the optimized land planning scheme more realistic.

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