A land use optimization model of the multimodal passenger transportation hub on TOD mode based on strategy analyses

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Abstract. With the acceleration of urbanization, Station City integration and TOD mode have become the mainstream of the multimodal passenger transportation hub construction. Based on the single factor analyses of SWOT, this paper puts forward a cross factor analyses method which is suitable for the multimodal passenger transportation hub on TOD mode. Through three circle spatial structure and taking the plot ratio of various types of land as decision variable, the land use optimization model is established with the goal of maximizing public transport passenger flow, building good living and commercial conditions in the region and land value-added. Finally, this paper takes Beijing Fengtai station as an example. The results of SWOT analyses show that Fengtai station should focus on solving the problem of traffic distribution in the first circle, optimize the land use, form TOD area and promote land value-added in the second circle. The results of land use optimization model show that the current situation of residential land use around Fengtai station can meet the demand of TOD mode. However, the plot ratio of commercial and business land is low and the area is tight, so it is suggested to improve the plot ratio index of this types of land.

1. Introduction

With the rapid development of China's urbanization process, problems such as traffic congestion, environmental pollution, high commuting costs and unreasonable land use have become more and more serious[1]. An effective means to solve the above problems is to develop public transport vigorously. In this background, the concept of transit oriented development (TOD) has been widely recognized[2]. TOD refers to the high-density land development around the main hub. Generally, the walking friendly planning method is adopted to mix the facilities such as residence, business and entertainment within the range suitable for walking[3]. It is of great significance to promote land use efficiency, improve public transport share rate and release traffic congestion.

The multimodal passenger transportation hub is the passenger flow distribution center of a city, which plays an extremely important role in the regional and urban development. Since the hub areas collect and distribute passenger flow at the same time, the agglomeration effect will bring a variety of traffic conflicts. When the passenger flow distribution line is not coordinated with the surrounding traffic planning, the hub area is easy to become a serious "blocking point" of the city. As for the development of the surrounding areas of the multimodal passenger transportation hub, the State Council issued the "opinions on supporting the implementation of comprehensive land development in railway construction" [4] and "the guiding opinions on giving priority to the development of public transport in..."
cities"[5] and other policies, all push forward TOD mode and promote the comprehensive development of land around the multimodal passenger transportation hub.

At present, the research on TOD abroad is more thorough, and there are many successful experiences[6-8], which can be used as a reference for China’s TOD development. However, China’s TOD research is still mainly focused on the concept, meaning, role and foreign experiences of TOD planning. There are not many studies on land use around the station based on TOD mode[9-12], and less for the optimization of land use around the multimodal passenger transportation hub. According to the TOD developing trend and state, this paper puts forward a SWOT analyses method suitable for the development of multimodal passenger transportation hub on TOD mode. This paper also proposes the developing circle structure and a land use optimization model of the multimodal passenger transportation hub on TOD mode based on SWOT analyses.

2. Strategic analyses of the multimodal passenger transportation hub on TOD mode

Strategic (SWOT) analyses is a kind of strategic planning analyses method. It combines the strategy of self-development with the internal and external environment by determining its own strengths, weaknesses, opportunities and threats. This paper proposes a SWOT analyses method suitable for the multimodal passenger transportation hub on TOD mode, which includes four basic steps: target determination, SWOT factor analyses, factor cross analyses and strategy generation, as shown in Fig. 1.

The determination of the target should be combined with the function of the multimodal passenger transportation hub and the pattern of TOD mode. Based on the objective situation of TOD development in China[13] and the "3D" principle proposed by Cervero and kocklman[14], the developing target of the multimodal passenger transportation hub are summarized as follows: 1) evacuate passenger flow of the hub rapidly, relieve road traffic congestion; 2) form intensive, mixed function, green and livable TOD area; 3) promote the price of surrounding land and improve local revenue. In the specific planning, the determination of the target should be flexible and reasonable. It should consider the level of the city, the location of the hub, the surrounding developing state and the expected passenger flow and so on.

SWOT factor analyses should start with various factors that affect the successful practice of TOD mode, including policy environment, surrounding traffic conditions, land use mode and intensity, passenger flow of the hub and land adjustable space, etc. Generally speaking, favorable policy support, high mixing and intensive land use, and friendly walking environment are all positive factors for TOD mode development[8]; the coordinated development of the hub and surrounding areas, as well as the demolition and renovation of original facilities around the hub can bring opportunities for TOD mode development; contrarily, the increased passenger flow and the influence of railway segmentation will bring challenges to the traffic system around the hub, which is the weakness or threat factor for TOD mode development of the multimodal passenger transportation hub.

On the basis of single factor analyses, this paper puts forward the multi-factor cross analyses method of the multimodal passenger transportation hub on TOD mode, as shown in Fig. 2. Through the collision and analyses of various composite factors, a reasonable TOD developing strategy can be formulated.
3. "Three circles" spatial structure of the multimodal passenger transportation hub on TOD mode

Under TOD mode, the surrounding planning of the multimodal passenger transportation hub should be guided by the target determined by SWOT analyses. Combined with the expansion characteristics of "circle layer" presented by the multimodal passenger transportation hub [9], this paper proposes that the surrounding planning of the multimodal passenger transportation hub under TOD mode should be carried out according to the spatial structure of "three circles", as shown in Fig. 3.

![Figure 3](image)

The third circle

- The second circle
- The first circle
- The core area
- The TOD residential area
- The regional developing linkage area

The first circle is the core area of the multimodal passenger transportation hub serving for passengers. The main function is to realize the rapid evacuation of passenger flow of the hub and prevent the road traffic congestion in surrounding areas. Therefore, the layout of the first circle should be helpful to realize the rapid evacuation of passenger flow by using public transport, such as rail transit and ground conventional bus transit. It also needs to avoid the situation that a large number of vehicles flowing into the surrounding areas, which will bring a lot of traffic pressure. As the core area of the multimodal passenger transportation hub, the first circle layer should include the hub body, the square in front of the hub, the auxiliary rooms of the hub, the rail and bus stations, the taxi drop off area and the infrastructure for providing various services for passengers. The scale of the first circle should be determined according to the scope of the multimodal passenger transportation hub, the expected passenger flow and the way of passenger flow evacuation. In principle, it should be controlled within a reasonable range as far as possible to ensure the transfer efficiency of passengers and reduce the impact to the second circle layer.

The second circle is the living area serving for residents and travelers, which is TOD residential area. According to the travel distance between residents and the multimodal passenger transportation hub, the main body of the hub or the supporting rail transit station is defined as the center of the second circle layer, and the area within the radius of about 1km to the center is the range of the second circle. In the
second circle, efforts should be made to create a livable TOD residential area, such as promote land use with high intensity and mixing degree, build convenient public transport and friendly walking and riding environment, better meet the living and working needs of residents within the area, reduce unnecessary long-distance commuting and improve the share rate of public transport while reduce the using of private cars.

The construction of the multimodal passenger transportation hub is often a part of top-level design in regional development, so the third circle is the regional developing linkage area. The main function of the third circle is to coordinate the traffic organization of the hub in a larger scope, such as improve the service efficiency of the hub, realize the functional coordination between the hub area and the whole city. The strategic goals of the third circle is to improve the regional status of the city and expanding the radiation energy. Since the third circle is an area that can provide any service for passengers and residents at any position in the city without time and distance limits, the boundary of the third circle is open.

In the planning process, the theoretical scale of each circle should be adjusted according to the construction target, urban characteristics and boundary conditions of the hub. Among the three circles, the first and the second circle are directly affected by the hub, which is also the research area of the land use optimization model on TOD mode in this paper. The third circle layer exists relative to the first and the second circle, it’s significance lies in a better understanding of the functions and scope of the first and second circle layers.

4. Land use optimization model of the multimodal passenger transportation hub on TOD mode

4.1. basic assumptions

Since the function of cities in the third circle are not directly related to the multimodal passenger transportation hub, and the boundary of the third circle is open, therefore the research scope of the land use optimization model on TOD mode is in the first and second circle, which is about 1km around the hub.

The conclusion of the case study on the planning of business types around the multimodal passenger transportation hub shows that the land development around the hub under TOD mode should be carried out in three formats: residential, commercial and public types. According to the standard of urban land classification, planning and construction (GB 50137-2011), the land types selected in this paper are: residential land R2, residential land R3, commercial land B1, business land B2, and public service land A (including A1-A9, public facilities land U, green land and square land G). The constructing of the model should combine with the results of SWOT analyses. It is assumed that the current land use value of each types in the region is known, and passengers who travel by rail transit or ground bus transit in the region all choose the station within the region as the starting point.

4.2. objective functions and constraints

The plot ratio as a comprehensive control index of urban land use, it is different from the shape control indicators such as building height and building density. The plot ratio is calculated by ratio, which is simple and easy to operate. The calculation results can partly reflect the fitness of the current land occupation area of various land types. In this paper, the plot ratio of each land types is used as the decision variable. The land use optimization model includes three objective functions, which are to maximize the passenger flow of public transport, create livable living conditions in the region and maximize the land value-added. The established objective function is shown in equations (1) to (3).

\[
\text{Max } Z_1 = (k + p) \sum_i X_i^r S_i^r T^r + (k + p) \sum_j X_j^b S_j^b T^b \]

\[
\text{Max } Z_2 = \sum_i X_i^r S_i^r + \sum_j X_j^b S_j^b \]

\[
\text{Max } Z_3 = \sum_i X_i^r Y_i^r + \sum_j X_j^b Y_j^b \]
In the equations, $Z_1$ is to maximize the passenger flow of public transport; $Z_2$ is to create a livable living conditions in the area; $Z_3$ is to maximize the land value-added; $X_i^r$ is the plot ratio of class $i$ residential land ($i=2,3$); $X_j^b$ is the plot ratio of class $j$ commercial land ($j=1,2$); $S_i^r$ is the area of class $i$ residential land, 100 square meters; $S_j^b$ is the area of class $j$ commercial land, 100 square meters; $S^a$ is the area of all kinds of public service land, 100 square meters; $k$ is the share rate of urban rail transit; $p$ is the share rate of ground conventional bus; $T_i^r$ is the traffic occurrence /attraction rate of residential land, person-time/hundred square meters; $T_j^b$ is the traffic occurrence /attraction rate of commercial land, person-time/hundred square meters; $Y_i^a$ is the percentage of value-added per unit building area of class $i$ residential land; $Y_j^b$ is the percentage of value-added per unit building area of class $j$ commercial land.

The constraints of the objective function include: plot ratio limit; the area of various public land to meet the living needs of residents in the region; residential land to meet the needs of regional development; public and commercial land to meet the needs of regional development, as shown in formulas (4) to (9).

\begin{align}
    l_i^r & \leq X_i^r \leq u_i^r, \quad i=2,3 \quad (4) \\
    l_j^b & \leq X_j^b \leq u_j^b, \quad j=1,2 \quad (5) \\
    l^a & \leq X^a \leq u^a \quad (6) \\
    S^a & \geq c \sum_i X_i^r S_i^r \quad (7) \\
    \sum_i X_i^r S_i^r & \geq d \left( \sum_i X_i^r S_i^r + X^a S^a + \sum_j X_j^b S_j^b \right) \quad (8) \\
    X^a S^a + \sum_j X_j^b S_j^b & \geq e \left( \sum_i X_i^r S_i^r + X^a S^a + \sum_j X_j^b S_j^b \right) \quad (9)
\end{align}

In the formulas, $l_i^r$ is the lower limit of plot ratio of class $i$ residential land; $u_i^r$ is the upper limit of plot ratio of class $i$ residential land; $l_j^b$ is the lower limit of plot ratio of class $j$ commercial land; $u_j^b$ is the upper limit of plot ratio of class $j$ commercial land; $c$, $d$, and $e$ are the demand-quantity relationship coefficients, which should be adjusted according to the results of SWOT analyses and the actual situation of land use around the hub.

4.3. model solving

The second objective function in the model is a nonlinear function, which can be converted into the linear function as shown in equation (10).

\[
    \min Z_2' = \frac{\sum_i X_i^r S_i^r + X^a S^a + \sum_j X_j^b S_j^b}{S^a} \quad (10)
\]

Then, the above models are sorted into multi-objective linear models, as shown in equation (11).

\[
    \min Z_4 = f_1 Z_1 + f_2 Z_2' + f_3 Z_3 \quad (11)
\]

s.t. (4)--(9); $X_i^r, X_j^b, X^a \geq 0$, $i=2,3$, $j=1,2$; $c$, $d$, $e > 0$

In the formulas, $f_1$, $f_2$, $f_3$ are the weight factors.

Equation (11) is the land use optimization model of the multimodal passenger transportation hub constructed in this paper. It can be known that the model is a linear multi-objective model, which can be solved by using the linprog function of MATLAB. Linprog function can be used to solve the minimum value of the objective function, and its algorithm principle is the improved projection method of simplex method. This method is that in solving the multi-objective model, the weight coefficient is given to each objective according to the importance of each objective, and the multi-objective problem is transformed into the problem of weighted sum of all objectives. The weighted objective function, equality and inequality constraints are used to construct the matrix respectively, and then a set of non inferior solutions can be obtained by using function grammar.

5. A case study: Beijing Fengtai station

5.1. overview of the study area and determination of parameters

Beijing Fengtai Station is located in the south of Fengguan Road, east of Fengtai East Street, north of
Fengtai East Road, between the third West Ring Road and the fourth West Ring Road, about one kilometer to the east of the old Fengtai railway station. It is one of the seven planned multimodal passenger transportation hub in Beijing. About three kilometers to the northeast of Fengtai Station is the Lize financial and business district, which is the emerging financial industry cluster area and the financial reform pilot zone of the capital as indicated in the overall urban planning of Beijing (2016-2035). At present, the land type around Fengtai station is mainly residential land, with many high-rise buildings and large population density, as shown in Fig. 4. The commercial land nearby is insufficient, and the plot ratio is low, which is difficult to meet the needs of residents for work and entertainment. It is easy to generate unnecessary long-distance commuting, resulting in road traffic congestion and waste of time in peak hours.

Figure.4 Schematic diagram of land type around Fengtai station

Using the SWOT analyses method put forward by this paper to analyze the TOD developing mode of Fengtai station. According to the function orientation and surrounding conditions of Fengtai station, the objectives are as follows: ① avoid regional road traffic congestion; ② build TOD area with maximum use of public transport and intensive use of land; ③ increase the government's financial revenue. According to the analysis, the advantages of TOD development of Fengtai Station are: ① favorable policy support; ② convenient and dense rail transit. The disadvantages of TOD development are as follows: ① the mixing degree of land use is low; ② the intensity of land development is low. The opportunity for TOD development is: the demolition and reconstruction work provides opportunities for optimizing land use. The threat of TOD development is: the induced passenger flow will bring pressure to the surrounding road network. Combined with the cross analyses of SO, ST, WO and WT factors, the TOD developing strategy of Fengtai station can be obtained.

SO cross analyses: make use of policy support to carry out a new round of comprehensive development around the hub based on TOD mode;
ST cross analyses: maximize the use of rail and ground public transport to realize rapid evacuation of passenger flow;
WO cross analyses: optimize the land use in the new round of development, and focus on improve the land use mix degree and developing intensity;
WT cross analyses: reduce the traffic pressure through the reasonable spatial layout around the hub, and realize the proper land use form.

Through the summary and analysis of the cross analyses results of various factors, the circle planning and strategy of TOD development of Fengtai station are obtained: ① In the first circle, make full use of the rail transit and the interchange connected with the station building and the surrounding third and fourth ring road to realize the rapid passenger flow evacuation. ② In the second circle, optimize the land use in the comprehensive development, focus on building an intensive, abundant and livable land use form around the hub. Strengthen the linkage with Lize business district in terms of traffic organization, promote the coordinated development of the region and maximize the land value-added. The results of the circle planning are shown in Fig. 5.
According to the results of SWOT analyses, the first circle layer (yellow area in Figure 5) and the second circle layer (orange area in Figure 5) around Fengtai station are taken as the research objective of this paper. According to the investigation, referring to the literature [11],[15] and Beijing local standards such as "Standard for land conservation in urban construction of Beijing", all the known parameters of this optimization model are obtained, as shown in Table 1.

### Table 1  Known parameters of land use optimization model

| parameters | Parameter value |
|------------|-----------------|
| $S^2_1$    | 3271            |
| $S^2_3$    | 1132            |
| $S^2_4$    | 954             |
| $S^2_5$    | 431             |
| $S^a$      | 543             |
| $k$        | 0.6             |
| $p$        | 0.2             |
| $\tau^r$  | 7.5             |
| $\tau^b$  | 7.5             |
| $Y^a_1$    | 20.3%           |
| $Y^a_2$    | 15.4%           |
| $Y^b_1$    | 15.4%           |
| $Y^b_2$    | 23.01%          |
| $t^l_1$    | 1.6             |
| $u^l_1$    | 2.8             |
| $t^b_1$    | 1.0             |
| $u^b_1$    | 4.0             |
| $t^a$      | 0.8             |
| $u^a$      | 1.6             |
| $c$        | 0.07            |
| $d$        | 0.35            |
| $e$        | 0.45            |

5.2. optimization results and analysis

Put all known data into the optimization model, and take the weight coefficient $f_1=f_2=f_3=1$, using the linprog function of MATLAB to solve $Z_4$, the non inferior solutions are obtained: $X^a_1=1.82$; $X^a_3=1.60$; $X^b_1=4.00$; $X^b_2=4.00$; $X^a=1.49$. take the optimization results compared with the current plot ratio, as shown in Table 2.

### Table 2  Comparison of plot ratio before and after optimization

| Land use types | Current plot ratio | Optimized plot ratio |
|----------------|--------------------|----------------------|
| R2             | 2.35               | 1.82                 |
| R3             | 0.65               | 1.60                 |
| B1             | 1.87               | 4.00                 |
| B2             | 1.72               | 4.00                 |
| A              | 0.95               | 1.49                 |
Comparing the plot ratio before and after optimization, it can be seen that the plot ratio of class 2 residential land R2 is 1.82 after optimization, which is less than 2.35 before optimization, indicating that the area of class 2 residential land in the region is sufficient to meet the needs of regional development, and it is not recommended to adjust class 2 residential land. The plot ratio of class 3 residential land R3 is 1.60 after optimization. However, the class 3 residential land around Fengtai station are mainly shantytowns to be demolished and reconstructed. According to the functional orientation of Fengtai station, it is not recommended to optimize the plot ratio of class 3 residential land. It is suggested to adjust the land type of class 3 residential land, it’s better to increase the area of commercial land, business land and public service land. After optimization, the plot ratio of commercial land B1 and business land B2 are 4.0, reaching the upper limit of Beijing standard, which reflects the shortage of commercial and business land area around Fengtai station, so the plot ratio standard of commercial and business land should be improved. After optimization, the plot ratio of public service land is 1.49, which is close to the upper limit of 1.6. It indicates that under the current land use condition, public land also needs high-intensity development to meet the living environment needs of residents in the region.

6. CONCLUSION
The road traffic congestion caused by induced traffic demand should be considered in the construction of the multimodal passenger transportation hub. TOD mode is an ideal mode for the coordination of the multimodal passenger transportation hub and surrounding land use development. Based on the factors influencing the successful practice of TOD mode and the objective situation of the multimodal passenger transportation hub, this paper puts forward the SWOT analyses method and the three circle spatial structure of the multimodal passenger transportation hub on TOD mode, and the land use optimization model based on the SWOT analyses and the three circle spatial structure, then makes a case study on Beijing Fengtai station. The method and model can not only provide a basic reference for the planning and construction of the hub, but also help planners to adjust the land types and optimize the plot ratio around the multimodal passenger transportation hub.

Acknowledgment
Innovative research group project of National Natural Science Foundation of China: "Theory and method of integrated transportation system management in urban agglomerations" (approval No.: 71621001)

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