Function Area Spatial Layout Method of Large High-Speed Rail Hub

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Abstract—Physical space of large high-speed rail (HSR) hub is the foundation of passenger aggregation, distribution and transfer. The spatial layout method of its function areas is the research hotspot in the field of transportation hub design. Aiming at the goal of minimizing the pedestrian walking distance, a spatial layout method for function area based on pedestrian flow of high-speed rail hub has come up. According to the characteristics of passenger activity and movement, the hub space is divided into different function areas macroscopically. Combined with case analysis, the general steps of the spatial layout method of high-speed rail hub and effectiveness of this method are illustrated.

1. INTRODUCTION

With the rapid development of HSR in China, it becomes more and more important for medium and long distance travel. As the core node of the city's external and internal traffic, the rationality of its function area layout, determines whether the core functions of the hub, passenger flow distribution and transfer are convenient and efficient, determines the overall operation efficiency and service level of the hub. Zhang Q. introduces the concept of space syntax, and puts forward the combination requirements of spatial layout of traffic functions from the perspective of building spatial correlation, to determine the core area in the hub space and develop the layout around it [1]. Xie Z. points out the shortest transfer distance, the optimization of information service and transfer space, and the integration of traffic facilities and urban functions are the keys, by summarizing the experience of the design and layout of the passenger traffic hub in Japan [2]. Zhao L. takes the integrated correlation degree among the hub facilities as the index, the facility layout was optimized and solved [3].

Relevant studies focus on the spatial layout of the hub at a single level, such as the layout of transfer or commercial facilities, without fully considering the nodes where pedestrian flow passes. Therefore, the current theory of function area layout is not refine enough. This paper starts from types of function areas in the hub and the pedestrian flow lines within it, taking pedestrian walking distance as the optimization goal, a spatial layout method of function areas based on pedestrian flow lines is proposed.
2. FUNCTION AREA AND PEDESTRIAN FLOW ANALYSIS

2.1. Function Area

2.1.1. Definition of Function Area
Passengers in the hub carry out the core transportation activities namely aggregation, distribution and transfer. Meanwhile they carry out the derived activities such as consumption. The areas that produce the above activities are the macro function areas of the high-speed rail hub.

Function areas can be divided into two types according to the nature of passenger service and their position at the node of pedestrian flow. The first one is the distribution area, which mainly serves railway transport, including entrance and transfer hall. The second one is the transfer area, which connects the railway transport, including rail platform, metro hall, bus station yard, taxi station yard, private car parking and so on. In this paper, the layout of the macro-function areas is studied, and the macro-passenger flow transfer between the above functional areas is mainly considered, while the micro-activities and flow lines within each function area are not considered.

2.1.2. Scale of Function Area
According to the definition of the function area in this paper, the nature of two types area is different. Based on the passenger distribution and transfer, the scale calculation method is given respectively.

First, the scale of distribution area is determined by its peak hour passenger volume \( Q_{ph} \). Based on design regulation and project practice, the minimum per capita area \( s_{min} \) is given. Thus the scale is \( s_{min} \cdot Q_{ph} \).

Second, the scale of transfer area is also determined by its peak hour passenger volume \( Q_{ph} \), along with turnover rate \( \varphi_{turn} \), vehicle unit area \( s_{veh} \), average passenger capacity \( N_{cap} \). Thus the scale is \( (Q_{veh} \cdot s_{veh}) / (\varphi_{turn} \cdot N_{cap}) \).

2.2. Flow Line Construction
On the basis of defining the types of function areas in a HSR hub, pedestrian flow lines generated between different areas are analyzed to determine the logical connection relation of each function area.

The source points of passenger flow producing and attracting within the scope of the hub are actually the station yard of the main traffic mode and the traffic mode connecting it. The macroscopic representation of pedestrian flow in a hub is the transfer flow line between them. In order to detailing route of flow line, and more accurately grasp the rationality of function area layout, according to the logical pedestrian activities and project practice, function area nodes in the hub are added reasonably on the flow lines with the transfer area as the end nodes. Define distribution areas as set \( S \), and transfer areas as set \( T \), the pedestrian flow lines set are constructed as \( path = T_i - S_0 - S_1 \cdots - S_n - T_j \).

3. FUNCTION AREA LAYOUT MODEL

3.1. Layout Principles

3.1.1. Intensive Use of Land
Considering the long-term urban development and TOD construction around HSR hub, no matter the hub is located in the downtown or suburban area, the spatial layout design should be compact and the land use should be intensive, so as to improve the utilization rate of the hub space, reserve space for future, and reduce the cost of construction.
3.1.2. Concise Design of Flow Line
Design pedestrian flow lines from the perspective of passenger travel, to guide the spatial layout. Pedestrian flow lines should be simple, convenient and non-intersecting. The inflow and outflow of the hub should be separated in space and the passenger flow should be separated in multiple directions. Thus, the distance of entering and leaving the hub, and transfer is reduced.

3.1.3. Public Transport Priority
Following the principle of public transport priority, the transfer distance between modes of public transport should be short. Therefore, the fast and efficient distribution of passenger flow in the hub can be ensured. The turnover efficiency of the hub can be improved, and the possibility of congestion and trampling within the hub space can be reduced.

3.2. Model Formulation
A function area spatial layout model is formulated, where the objective is to minimize the weighted pedestrian walking distance. In order to model this problem, we make assumptions as follows:
- The number, station yard, and transfer demand volume of hub transfer modes are known.
- The platform boundary and the central coordinates are known.
- Each function area is rectangular in shape.
- Taking the center of the general plane of the hub platform as the origin of coordinates, the long axis as the X-axis and the short axis as the Y-axis, and introducing the floor integer variable, the space coordinate system is constructed.
- The pedestrian study object in the function area only considers the passengers, not the staff.
- The walking distance between the function area nodes consist of plane and vertical distance. The plane distance adopts the Manhattan distance. The vertical distance is multiplied by the reduced coefficient, which is the vertical amplification coefficient.

Thus, the optimization problem of function area spatial layout is

\[
\text{Minimize } \sum_{i \in C_i} \sum_{j \in C_j} \text{length}_{ij} \cdot \text{flow}_{ij} \quad (1)
\]

\[
\text{length}_{ij} = \sum_{\text{path } i \in path_i} \sum_{\text{path } j \in path_j} |x_i - x_{i+1}| + |y_i - y_{i+1}| + |f_i - f_{i+1}| \cdot v \quad (2)
\]

Subject to

\[
[(x_i - \frac{l_i}{2}) - (x_j + \frac{l_j}{2})] \cdot [(x_i - \frac{l_i}{2}) - (x_j + \frac{l_j}{2})] \cdot [(y_i - \frac{w_i}{2}) - (y_j + \frac{w_j}{2})] \cdot [(y_i - \frac{w_i}{2}) - (y_j + \frac{w_j}{2})] \leq 0 \quad (3)
\]

\[
r_{\text{min}} \leq l_i / w_i \leq r_{\text{max}} \quad (4)
\]

\[
\text{area}_{\text{min}} \leq l_i \cdot w_i \leq \text{area}_{\text{max}} \quad (5)
\]

Equation (1) is the objective function, which indicates the weighted pedestrian walking distance should be minimized. (2) states how the length of a flow line is calculated. (3) states that if area and area are located in the same floor, then they cannot be overlapping. However, metro hall and the transfer hall are the exception. (4) and (5) ensures that the ratio of length to width and the size of area of each function area are limited within a reasonable range.

3.3. Model Solution
Because of a large number of model variables and constraints, a differential evolutionary algorithm with stronger global convergence and higher robustness than the traditional genetic algorithm is adopted in this paper to solve the optimal layout of hub function areas.

3.3.1. Variable Coding
The decision variables of the model are composed of function area central coordinates, the dimensions of the length and width, and the floor code. The method of real coding is adopted, which can convert
directly to a gene on a chromosome without decoding

3.3.2. Fitness Evaluation
The fitness function is used to evaluate the merits and demerits of each chromosome in each generation of the population in the evolutionary process, so as to determine whether it is inherited to the next generation.

3.3.3. Genetic Operation
Three individuals were randomly selected from initial population to generate mutant individuals according to certain rules. The new individuals were directly generated by crossing with the parent individuals, and the individuals were selected according to the fitness.

4. CASE STUDY
Beijing South Railway Station is selected as a case study. It is located between south second ring road and south third ring road. By collecting the transfer passenger flow data and space limit of the hub's building, using the function area layout model, the optimal layout plan can be achieved. Compared with current layout plan, the effectiveness of the function area layout method based on pedestrian flow can be verified.

4.1. Case Data
The hub’s main mode of transportation is railway, while its transfer modes consist of metro, bus, taxi and private car. According to the definition of function area, the distribution areas consists of the entrance hall, waiting hall and transfer hall, while transfer areas consist of railway platform, metro hall, bus station yard, taxi waiting area, social parking lot and car drop-off area.

Based on the data collected by Kang H. shown in table 1, the passenger transfer volume between different modes of transportation in Beijing South Railway Station on a working day in 2015 were adopted [4]. The passenger flow of taxi plus private car transferring to the railway is classified to the car type. Thus the transfer passenger flow matrix is formulated as shown in table. The volume of peak hour passenger flow is calculated as 20870 people per hour according to the train schedule.

| TABLE 1. TRANSFER PASSENGER FLOW MATRIX(10 THOUSAND) |
|-----------------|----------------|----------------|----------------|----------------|
| Rail            | Metro          | Bus            | Taxi           | Private        |
| Rail            | 0              | 5.6079         | 2.3715         | 2.6226         | 1.2276         |
| Metro           | 4.2129         | 2.2599         | 1.7298         | 0              | 0              |
| Bus             | 2.4552         | 0.8649         | 0.7254         | 0              | 0              |
| Car             | 3.8223         | 0              | 0              | 0              | 0              |

According to the calculation method of function area scale, the peak hour passenger flow is calculated through the passenger flow matrix in Table, thus the size area range is calculated.

Meanwhile, the function area scales of the hub were investigated to determine the scale range of each function area. Finally, the basic constraints of the layout model were obtained as shown in the table 2. The platform is considered as a known area, and the plane coordinates of the waiting hall and the transfer hall center are consistent with the platform, which are (0,0). The waiting hall and entrance hall are set in F2, and the metro hall is set in B1. To facilitate the show, the function areas are numbered as below: ①platform, ①entrance hall, ②waiting hall, ③transfer hall, ④metro hall, ⑤bus drop-off, ⑥bus pick-up, ⑦taxi waiting area, ⑧social parking, ⑨car drop-off.

| TABLE 2. LENGTH TO WIDTH RATIO, AREA RANGE AND FLOOR |
|-----------------|----------------|----------------|----------------|
| Area            | Rate           | Area/m²        | Floor          |
| ①               | [0.8,1.2]      | [4174,5009]    | F2             |
| ②               | [0.6,1.6]      | [25044,30053]  | F2             |
4.2. Analysis Of Flow Line

Through transfer passenger flow matrix analysis and field research, the internal transfer types at the same location and transfer types with minimal amount were eliminated. Thus, ten effective transfer pairs are obtained. The function areas through which the flow line passes are added to form ten hub macro pedestrian flow lines, as shown in table 3.

| TABLE 3. HSR HUB MACRO PEDESTRIAN FLOW LINES |
|------------------------------------------------|
| 1 Rail-Metro | ○ - ○ - ○ |
| 2 Rail-Bus | ○ - ○ - ○ |
| 3 Rail-Taxi | ○ - ○ - ○ |
| 4 Rail-Private | ○ - ○ - ○ |
| 5 Metro-Rail | ○ - ○ - ○ / ○ - ○ - ○ - ○ - ○ |
| 6 Metro-Bus | ○ - ○ - ○ |
| 7 Bus-Rail | ○ - ○ - ○ / ○ - ○ - ○ - ○ - ○ |
| 8 Bus-Metro | ○ - ○ - ○ |
| 9 Bus-Bus | ○ - ○ |
| 10 Car-Rail | ○ - ○ |

4.3. Optimal Layout Calculation

According to the transfer passenger flow matrix and constraints of function areas for the layout, setting the population size as 150, maximum evolutionary generation as 5000, differential evolutionary variational scaling factor as 0.5, and recombination probability as 0.7, by programming in Python, the function area layout model can be solved out. After running several times, one satisfied solution is obtained. The center coordinates, floor variable, length and width of the function areas are calculated and shown in table 4.

From the running steps of differential evolution algorithm shown in Figure 2, the convergence speed of the algorithm is very fast around 300 generations, which proves the effectiveness of this algorithm. The objective function value is 3281, while the value of original plan is 3520, which proves the rationality of the optimal plan and this algorithm for solving the problem.

Finally, the function areas layout plan is shown in Figure 1. The transfer hall, platform, and waiting hall is set separately in B1, F1, and F2. The transfer areas layout shows consistency with the current layout to a certain degree, while the bus drop-off area and social parking lot is set in F2.

| TABLE 4. CENTER CORONDATE, SIZE AND FLOOR OF FUNCTION AREA |
|----------------------------------------------------------|
| Area | X(m) | Y(m) | L(m) | W(m) | Floor |
| ☒ | 0 | 0 | 250 | 180 | 0 |
| ☒ | -124 | -19 | 54 | 42 | 1 |
| ☒ | 0 | 0 | 194 | 147 | 1 |
| ☒ | 0 | 0 | 239 | 192 | -1 |
| ☒ | 0 | 0 | 85 | 82 | -1 |
| ☒ | -116 | 14 | 31 | 24 | 1 |
5. CONCLUSION
Based on the macro pedestrian flow lines within the HSR hub, a method to solve the optimal layout of macroscopic function area is proposed. By dividing the function areas into distribution areas and transfer areas, the former one served as the intermediate point of flow line, the latter served as the endpoint of flow line, the pedestrian flow lines in space are constructed. Next the calculation method of function area scale is proposed. Taking the amount of flow as the weight, the weighted walking distance of passengers as the objective function, the differential evolution is used to solve the problem.

Compared with the current layout plan, a satisfactory plan is obtained, which verifies the practicability of the model, breaking through the current rigid thinking of HSR hub and other station design in China, and providing a new idea for the function area layout. The outcome of the model shows that the future HSR hub must develop towards a integrated hub, rather than the current traffic hub, which restricts the overall layout mode of the hub.

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