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Optimization Method of Transfer Streamlines in Integrated Passenger Hubs Based on 3D Spatial Perspective

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Abstract: To optimize the functional space layout of various transportation modes of the integrated passenger transport hub, and improve the transfer efficiency and service quality of the hub, a quantitative analysis of the transfer flow lines of the integrated passenger hub is carried out. The research clarifies the layout factors of the functional areas of the "get on and drop off areas" for each mode of transportation, generates a candidate set of the placement of each functional area, and determines the priority ranking of the candidate sets and the transfer starting and end locations. Based on the analysis of passenger route selection factors, the basic transfer streamline network is generated. The basic network is distributed according to the improved shortest path allocation algorithm, and the relevant parameters are calculated to simplify the initial transfer streamline network, generate and compare the initial network plan of the transfer streamline. Take Wuxi Integrated Passenger Transport Hub as an example to verify: when the weight coefficient $\lambda = 0.65$ and the number of allocations $n = 207$, the optimal solution T = 2,738,027 s is obtained. As the calculation is based on the 15,000 passenger transfer flow at Wuxi Station, the optimized average transfer time per person is 3 min 2 s. Compared with the current average transfer time per person at Wuxi Station of 4.5 min, the optimization effect of this paper is significant. The initial network generation and comparison method of the transfer flow line enables the space layout of the transportation modes of the hub to be coordinated with the transfer flow line design, and solves the problem of the transfer flow line design when the hub building space layout is determined. The hub is designed to meet the requirements of functional space layout, passenger transfer needs and interchange efficiency at the initial stage of architectural design.

Keywords: integrated passenger transport hub; transfer streamline; shortest path algorithm; network traffic distribution; generalized impedance model

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1. Introduction

Comprehensive passenger transport hubs are systemic and complex, mainly reflected in the diversification of transportation modes and diversification of functions [1,2]. In addition, the main body of the architectural design and traffic design of the integrated passenger transport hub is different, and there is often a lack of systematic consideration and reservation of the transfer flow line, resulting in poor connection and fragmentation of the transport modes of the hub. Therefore, a reasonable and detailed transfer flow line design is one of the key issues in the design of a comprehensive passenger transport hub [3,4].

In the past several decades, traffic designers, planners and scholars have paid much attention to the transfer flow line organization, optimization and transfer flow distribution. O'Kelly et al. established an analysis framework for the transfer process in the hub, and proposed an optimization model for facility resource design [5]. Flurin et al. proposed a prediction model for pedestrian demand inside the railway station based on passenger volume, passenger flow density and historical data [6]. Yuen et al. put forward an intelligent algorithm to predict the route choice behavior of passengers, and verified the applicability of the intelligent algorithm by optimizing the number of entrances and exits in transportation hubs [7]. Mei proposed a binary linear programming method to improve the design of identification systems in various enclosed environments such as airport terminals, multi-functional train stations and shopping malls [8]. Rocha et al. proposed a data-driven framework for the configuration and capacity estimation of transfer facilities to predict the intensity of airport passenger flow [9]. Xia broke through the constraints of traditional transfer streamline analysis and proposed a streamline design method based on the superposition of multiple transportation modes in a three-dimensional network space [10]. Daamen et al. built a passenger route selection model in the hub based on the shortest path algorithm applying data collection and passenger flow characteristic analysis [11]. Solak et al. established a multi-stage stochastic planning model for the multi-user streamline design using analytical methods for the internal passenger streamline network of the airport [12]. Guo proposed a potential-based dynamic pedestrian flow allocation model, which optimizes the evacuation process of large-scale crowds and effectively recognizes the local congestion dynamics in the crowd evacuation process [13]. Porter et al. used a combination of social force models, behavioral heuristics and multi-stance concepts to establish a model framework that captures passenger walking behavior under crowded and non-crowded conditions [14]. Antoine et al. accurately predicted the dynamics of pedestrians in complex buildings by training and testing artificial neural networks [15]. Based on the relevant design data of high-speed railway stations, Duan et al. used the "Logit model" to predict the proportion of various travel modes in the future based on the connection principles, layout forms and traffic flow lines of different transportation modes to obtain the optimal hub layout [16]. Yuan established an equilibrium constraint model for the comprehensive design of the hub location and connection facilities in the multimodal transport network to improve the overall performance of the transportation-oriented system [17]. At the current stage of economic development, the construction of a modern transportation hub-HUB- plays a key role in the effective operation of the rail passenger complex, which will provide interaction between rail carriers and other participants in the passenger transport industry [18].

As shown in the literature review, previous studies mostly focused on the design of the transfer flow line and the partial optimization of the transfer flow line when the functional space layout has been determined. The spatial scope is a two-dimensional space, and the interaction between the function of the hub building and the flow line design is less considered. The three-dimensional spatial structure of the hub is difficult to adapt to the diversified passenger flow requirements and intensive functional space within the hub. Some scholars have applied the optimization of the transfer flow line network to guide the layout of the hub function space and the configuration of facilities and equipment, which is still in the stage of theoretical conception [19].

This paper combines the three-dimensional spatial structure of the comprehensive passenger transport hub, considers the transfer flow line network inside the hub, integrates transfer demand and transfer preferences into the transfer flow line design, employs the shortest path algorithm to guide the spatial layout and then uses the flow distribution method to calculate the spatial scale. The transfer flow line design and the architectural space design are carried out simultaneously, and the transfer flow line network design guides the functional space layout of the hub, which provides a new method for the collaboration of different professional designers of the hub. The optimization framework of the transfer streamline is shown in Figure 1.

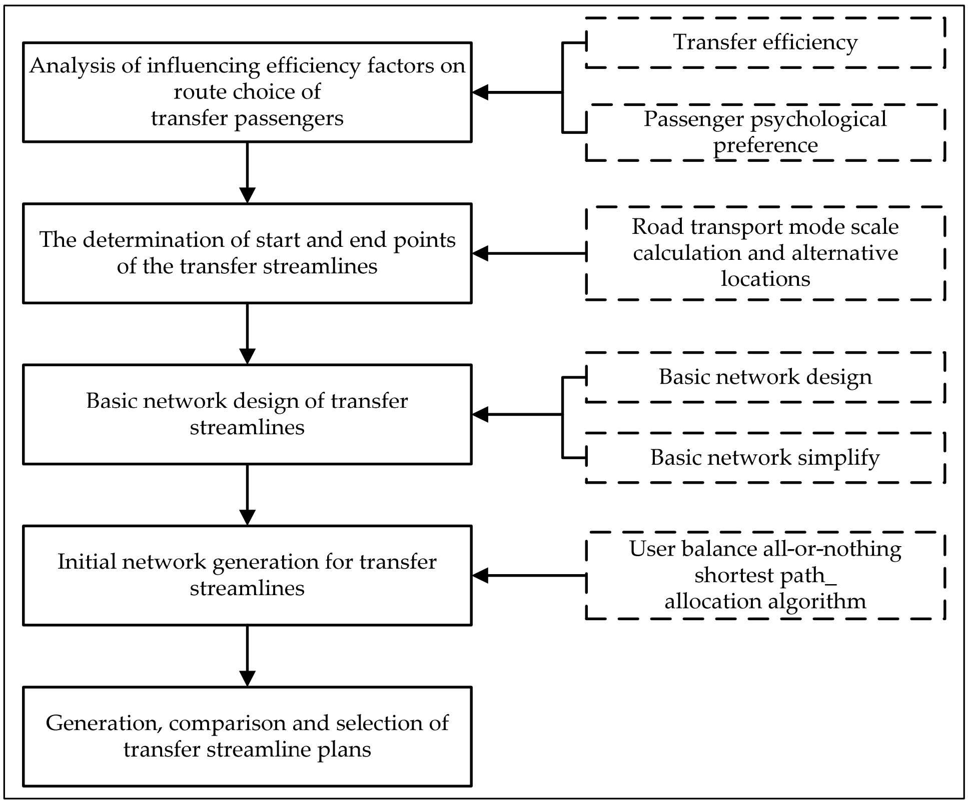


Figure 1. Framework diagram of the optimization method of transfer streamline.

2. Passenger Transfer Influence Factors and Process Demand Analysis

The factors that affect the choice of passenger transfer routes within the integrated passenger hub mainly include transfer time, transfer distance, guidance marking system, route turn times and passenger flow distribution on the route [20]. This paper focuses on transfer efficiency and passengers' psychological preference factors. The following two types of main factors are analyzed.

2.1. Transfer Influence Factors

2.1.1. Transfer Efficiency

Transfer efficiency is characterized by transfer time. Transfer time refers to the time required for passengers to realize the transfer. In the process of passenger transfer, conflict and delay will occur at the nodes where the flow lines intersect, resulting in a transfer time increase. The flow line design should shorten the passenger transfer time as much as possible. Therefore, when establishing the flow line optimization model, the overall goal is to minimize the transfer time of the passenger flow in the entire network system.

2.1.2. Passenger Psychological Preference

Passengers also have a preference for the shortest topological route when choosing a transfer route, that is, the route has the least number of turns. Because passengers psychologically simplify the transfer path to a straight line, and generate corresponding spatial perception and walking direction in the mind, this helps passengers use the shortest time and route to perceive the transfer path. Passengers will obviously prefer a route with fewer turns, which requires less turns in the transfer flow line to reduce the passenger's sense of confusion. Therefore, the number of turns needs to be considered when establishing the basic network of transfer flow lines.

2.2. Passenger Transfer Process Demand Analysis

2.2.1. Demand Parameter

Since the streamline design serves the traffic demand of dynamic traffic flow through static spatial sequence design, we selected the annual peak hour traffic volume to measure the "average level" of dynamic demand of traffic flow and this serves as the basis for determining process demand, as shown in Equation (1).

$$Q_L = f(q) \tag{1}$$

where Q_L is the Traffic carrying capacity of streamline L, person/hour; q is the design annual peak hour traffic volume in streamline space, person/hour.

2.2.2. Transfer Demand Representation

Transfer demand is expressed in the form of transfer process demand between different modes of transport, namely transfer traffic volume, whose annual peak hour traffic flow results can be expressed as a transfer matrix between different modes of transport. The form of transfer matrix is shown in Table 1. Through the transfer matrix, transfer passenger flow, flow direction, total arrival, total transmission and total transfer of various transport modes can be obtained.

Table 1. Transfer matrix (person/hour).

O \ D	1	2	3	4	5	6	7	8	9	Sum of D
1	A11	A12	A13	A14	A15	A16	A17	A18	A19	A1D
2	A21	A22	A23	A24	A25	A26	A27	A28	A29	A2D
3	A31	A32	A33	A34	A35	A36	A37	A38	A39	A3D
4	A41	A42	A43	A44	A45	A46	A47	A48	A49	A4D
5	A51	A52	A53	A54	A55	A56	A57	A58	A59	A5D
6	A61	A62	A63	A64	A65	A66	A67	A68	A69	A6D
7	A71	A72	A73	A74	A75	A76	A77	A78	A79	A7D
8	A81	A82	A83	A84	A85	A86	A87	A88	A89	A8D
9	A91	A92	A93	A94	A95	A96	A97	A98	A99	A9D
Sum of O	AO1	AO2	AO3	AO4	AO5	AO6	AO7	AO8	AO9	AOD

Notes: The numbers from 1 to 9 represent 9 various modes of transportation, namely, railway, roadway, urban rail transit, bus, taxi, social vehicle, non-motor vehicle, walk and other transportation. Among them, external transportation consists of railway, roadway, others are urban transportation. O and D represent the volume of arrival and departure, respectively.

The transfer volume involving walking means mainly refers to the passenger flows arriving at the hub on foot and going to other regions by other means of transport within the hub, as well as the passenger flows arriving at the hub from other regions and leaving the hub on foot. This part of passenger flow can be carried out through the prediction of travel production volume and travel mode structure proportion in the surrounding area of the hub.

3. Initial Network Generation Method for Interchange Flow Lines

3.1. The Determination of Start and End Points of the Transfer Streamline Network

3.1.1. Alternative Locations for Urban Rail Transit

The layout of urban rail transit stations is closely related to hub land conditions, track selection, engineering technical conditions and upper-level planning. Given that the layout and scale of the urban rail transit yard have been taken into consideration during the design of the hub scheme, the alternative areas of the passenger boarding and disembarking areas can be determined according to the design scheme.

3.1.2. Alternative Location for Road Transportation

Road transportation methods include long-distance buses, buses, taxis, private cars, non-motorized vehicles, etc., and the setting of the pick-up and drop-off area is more flexible, mainly affected by the hub land conditions, economic costs, the area of facilities required by each mode and the performance of the transport vehicles. Due to the limitation of factors, the following is the method for calculating the size of the pick-up and drop-off area in each mode.

(1) Long-distance bus

The boarding area of long-distance buses consists of the departure area, ticket hall, ticket office and waiting hall; the disembarking area can be set up by the space of the lane, including parking area, driving space and passenger evacuation area. The scale calculation of the pick-up area should be carried out regarding the specifications [21,22], and the scale calculation of the drop-off area can refer to Equation (2) [23], in which the parameters can be obtained by field investigation.

$$S_{ji} = \frac{\sigma \cdot N_i \cdot s_{ji}}{P_i \cdot L_i} + S_{xi} \tag{2}$$

S_{ji}: The drop-off area of transportation mode i, m^2
σ: Peak hour correction factor
N_i: Passenger flow of the i-th mode of transportation during peak hours, person-times/hour
s_{ji}: Passenger evacuation area or parking space per unit area, m^2
P_i: Average number of guests per vehicle, people/vehicle
L_i: The number of vehicles available for each drop-off seat in a unit hour, vehicles/hour
S_{xi}: Transportation mode i driving space area, m^2

(2) Regular bus

The passenger pick-up and drop-off area of a regular bus is composed of the parking area, driving space and platform space, which can be connected to pedestrian passages and flexibly distributed around the hub, but the needs of passengers for transfer distance must be considered. The scale calculation can refer to Equation (2).

(3) Taxi

Taxis generally use the side of the lane to disembark passengers, and the disembarkation area occupies a small space. The scale can be calculated by Equation (2). Because of its flexible layout, it can be deployed close to the core area of the hub. The taxi pick-up area is generally connected to the waiting area, and the scale can be calculated using Equation (3) [23]. The layout of the pick-up area needs to be comprehensively determined in accordance with the organization of vehicle operation and land use conditions.

$$S_{ci} = \frac{\sigma \cdot N_i \cdot s_{ci}}{P_i \cdot K_i} + S_{hi} + S_{xi} \tag{3}$$

S_{ci}: The pick-up area of transportation mode i, m^2
N_i: Passenger flow of the i-th mode of transportation during peak hours, person-times/hour
s_{ci}: Passenger waiting area or parking space per unit area, m^2
P_i: Average number of guests per vehicle, people/vehicle
K_i: The number of vehicles available for each boarding seat in a unit hour, vehicles/hour
S_{hi}: Transportation mode i parking space area, m^2
S_{xi}: Transportation mode i driving space area, m^2

(4) Private car

Private cars can use the side of the lane to disembark passengers. It is advisable to plan and set up the taxi disembarkation area together. The scale calculation can refer to

Equation (2). The passenger boarding area uses social parking lots, including parking areas and driving space areas, and the scale calculation can refer to Equation (4) [23].

$$S_{pi} = \frac{\sigma \cdot N_i \cdot s_{pi}}{P_i \cdot K_i} + S_{xi} \tag{4}$$

S_{pi}: The parking area of transportation mode i, m^2
N_i: Passenger flow of the i-th mode of transportation during peak hours, person-times/hour
s_{pi}: Unit vehicle occupied area, m^2
P_i: Average number of guests per vehicle, people/vehicle
K_i: The number of vehicles that can be parked in each parking space per unit hour, vehicles/hour
S_{xi}: Transportation mode i driving space area, m^2

(5) Non-motor vehicle

The passenger pick-up and drop-off area for non-motor vehicles is mainly composed of parking facilities, which are small in scale and can be flexibly arranged close to the core area of the hub. The scale calculation can apply Equation (4).

3.2. Initial Network Generation for Transfer Streamlines

In view of the fact that passengers prefer the shortest path in the metric system and the shortest topological path when choosing transfer routes, a basic network with the shortest transfer distance and large capacity covering all transfer destinations is first constructed. To simplify the basic network and make the transfer more in line with the needs of passengers, this paper adopts the common vertical route space and does not study the oblique passage.

The basic network of the transfer flow line has the shortest transfer distance and the least number of turns, including the start and end points of all transfer paths, as well as the mutually perpendicular route space. Using related concepts in graph theory, the basic network of the transfer streamline can be expressed as $W = (N, A)$, N is the nodes set, $N = \{N_i | i = 1, 2, \ldots, n\}$; A is the arc segments set, $A = \{a(N_i, N_j) | N_i, N_j \in N, a = 1, 2, \cdots, m\}$. The nodes and arc segments of a transfer path in the transfer streamline network are represented by the following symbols:

r: the starting point of a transfer route;
R: the starting point set of all transfer routes,$r \in R$;
d: the end of a transfer route;
D: the end point set of all transfer routes,$d \in D$;
p: intermediate node of a transfer route;
P: the set of intermediate nodes of all transfer routes, $p \in P$,$N = (R, D, P)$;
a: the arc segments connecting two intermediate nodes on a transfer path;
A: sets of arc segments on all transfer paths,$a \in A$.

Then the initial network of transfer flow lines inside the hub is generated as follows: a three-dimensional coordinate system is constructed inside the hub building space, and all transfer start points and end points correspond to three-dimensional coordinate values. For any transfer route, the coordinate of the start point r is (x_r, y_r, z_r), the coordinate of the end point d is (x_d, y_d, z_d), create nodes $p_1(x_d, y_r, z_r)$, $p_2(x_r, y_d, z_r)$, $p_3(x_r, y_r, z_d)$, $p_4(x_d, y_r, z_d)$, $p_5(x_d, y_d, z_r)$, $p_6(x_r, y_d, z_d)$, construct arc segments $a_1(r, p_1)$, $a_2(r, p_2)$, $a_3(r, p_3)$, $a_4(p_1, p_4)$, $a_5(p_1, p_5)$, $a_6(p_2, p_5)$, $a_7(p_2, p_6)$, $a_8(p_3, p_6)$, $a_9(p_3, p_4)$, $a_{10}(p_4, d)$, $a_{11}(p_5, d)$, $a_{12}(p_6, d)$, as shown in Figure 2.

With r as the starting point and d as the ending point, there are a total of six paths that are perpendicular to each other with the shortest transfer distance and the least number of turns. Excluding the vertices r and d, the remaining nodes are the intermediate nodes of the path, and each intermediate node is connected by a corresponding arc segment, and each shortest path contains three arc segments.

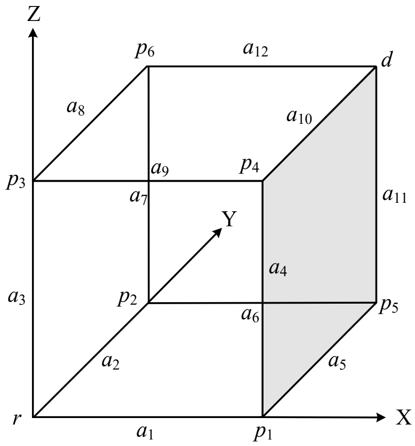


Figure 2. Schematic diagram of generation of basic network nodes and arc segments.

The basic network diagram is shown in Figure 3. Corresponding intermediate nodes and arc segments are established for all transfer paths, and a relatively complex three-dimensional space network is generated, which is composed of the start and end points of the transfer path, the intermediate nodes of the transfer path and the connecting arc segments between the intermediate nodes. This network is a collection of the shortest paths between the start and end points of each transfer.

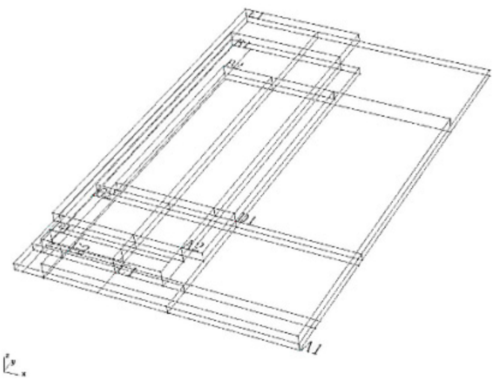


Figure 3. Schematic diagram of generation result of basic network.

For the actual hub flow design, the base network diagram generated by the above methods is often too many and too dense. Therefore, the nodes and arc segments in close proximity can be merged and simplified to obtain a simplified base network, which is more in line with the scale and needs of the actual flow channel. The network simplification is achieved by clustering the coordinates of each node on the *X* and *Y* coordinate axes, the *Z*-axis coordinate is unchanged, and the arc segments connection relationship between nodes is unchanged either. Generally speaking, if the total number of all nodes in the network is greater than 50, and the number of classifications is relatively certain, the K-Means clustering method can be used. Specific steps are as follows:

① Select two parallel and appropriate spacing channels inside the hub, read the *X* coordinates of all nodes and select different cluster numbers K for K-Means clustering.

② Change the *X* coordinate value of each node to the average value of its category.

③ Perform the *X*-axis operation on the *Y*-axis coordinate of each point, the same steps as ① ②, and then change the *Y*-axis coordinate value of each point to the average value of its category.

④ The *Z*-axis coordinate value of each node remains unchanged, and the arc segments relationship remains unchanged.

The basic network can be simplified, as shown in Figure 4. The simplified basic network can meet the passengers' requirements for the minimum number of turns and the shortest distance, and the spatial network is relatively simple.

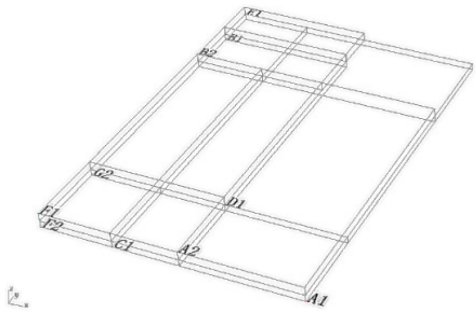


Figure 4. Schematic diagram of simplified basic network.

3.3. Transfer Streamline Network Generation Model

3.3.1. Model Establishment

(1) Symbol definition

On the basis of Section 3, a directed weighted graph is introduced in the initial network generation process of the transfer streamline, and the definition symbols are as follows:

k_{rd}: a transfer route between the starting point r and the ending point d;

K_{rd}: set of all paths between the transfer starting point r and the ending point d, $k_{rd} \in K_{rd}$;

q_{rd}: total passenger flow between transfer starting point r and ending point d;

q_{rd}^k: passenger flow on the k-th path between the transfer starting point r and the ending point d;

λ: weight coefficient, $0 \le \lambda \le 1$;

q_a^n: after the n-th passenger flow distribution, the total passenger flow on the arc segment a;

q_v^n: after the n-th passenger flow distribution, the total horizontal path passenger flow passing through node v;

s_a^n: before the n-th passenger flow distribution, the generalized impedance of arc segment a;

S_A^n: before the n-th passenger flow distribution, the generalized impedance set of all arc segments, $s_a^n \in S_A^n$;

s_v^n: before the n-th passenger flow distribution, the generalized impedance of node v;

S_V^n: before the n-th passenger flow distribution, the generalized impedance set of all nodes, $s_v^n \in S_V^n$;

S_G^n: before the n-th passenger flow distribution, the generalized impedance set of the entire network, $S_G^n = \left(S_A^n, S_V^n\right)$;

u_t: total number of path turns;

u_t^{max}: maximum number of turns;

b_a^n: after the n-th passenger flow distribution, the time cost of arc segment a, second;

B_A^n: after the n-th passenger flow distribution, the time cost set of all arc segments, second, $b_a^n \in B_A^n$;

b_v^n: after the n-th passenger flow distribution, the time cost of node v, second;

B_V^n: after the n-th passenger flow distribution, the time cost set of all nodes, second, $b_v^n \in B_V^n$;

B_G^n: after the n-th passenger flow distribution, the time cost set of the entire network, second, $B_G^n = \left(B_A^n, B_V^n\right)$;

$n_{\max}$: maximum number of passenger flow distribution.

(2) Objective function

Given that the time cost is more intuitive and easier to calculate quantitatively, the overall goal is to minimize the transfer time of the passenger flow in the entire network system, including the arc segment time cost and the node time cost, as shown in Equation (5).

$$\min_{1 \le n \le n_{\max}} T(n) = \sum_a b_a^n \cdot q_a^n + \sum_v b_v^n \cdot q_v^n \tag{5}$$

$T(n)$: objective function, the total transfer time cost of the entire network after the n-th passenger flow distribution;

$\sum\limits_a b_a^n \cdot q_a^n$: total transfer time cost of the arc segments;

$\sum\limits_v b_v^n \cdot q_v^n$: total transfer time cost of the nodes.

(3) Path selection model

Taking the minimum total generalized impedance of the path between the start and end points of each pair of transfers as the goal, a path selection model is established, as shown in Equation (6).

$$\min_{k_{rd} \in K_{rd}} H(k_{rd}) = \sum_{a \in k_{rd}} s_a^n \cdot q_a^n + \sum_{v \in k_{rd}} s_v^n \cdot q_v^n \tag{6}$$

$H(k_{rd})$: objective function, which means that the total generalized impedance on a transfer path between the transfer start point r and the end point d is the smallest;

$\sum\limits_{a \in k_{rd}} s_a^n \cdot q_a^n$: the total generalized impedance of the arc segments on this path;

$\sum\limits_{v \in k_{rd}} s_v^n \cdot q_v^n$: the total generalized impedance of the nodes on this path.

3.3.2. Calculate Generalized Impedance

Distribute the passenger flow between the transfer start and end points on the initial network of the transfer flow line. Passengers choose the path with the smallest generalized impedance value to transfer. After multiple passenger flow allocations and iterative optimizations, the transfer path plan is optimized and the passengers' cost is the smallest, and the initial network of transfer flow lines is generated at the same time. This paper adopts the user balance all-or-nothing allocation method, set weight coefficient $\lambda (0 \le \lambda \le 1)$, then the generalized impedance set of the network before the n-th traffic distribution is Equation (7).

$$S_G^n = (1 - \lambda) \cdot S_G^{n-1} + \lambda \cdot B_G^{n-1} \tag{7}$$

The generalized impedance on the entire network before the n-th passenger flow distribution is formed by the superposition of the generalized impedance after the $(n-1)$-th passenger flow distribution and the time cost of the $(n-1)$-th passenger flow distribution. It can be seen from Equation (7) that S_G^n is generated by B_G^n iteratively. Therefore, it is necessary to calculate the time cost b_a^n of a single arc segment and the time cost b_v^n of a single node after the n-th passenger flow distribution. B_G^n and S_G^n can be calculated step by step, and the generalized impedance can be analyzed by calculating the time cost of the arc segment and the node after the passenger flow distribution.

Time Cost of a Single Arc Segment

In view of the fact that a single arc can be divided into horizontal arc segments and vertical arc segments, which correspond to the horizontal transfer facilities and the vertical transfer facilities in the hub, the time costs of the two are different.

(1) Calculate the time cost of the horizontal arc segment

$$t_{ha} = L_{ha} / \overline{v} \tag{8}$$

t_{ha}: the time cost of the horizontal arc segment a, second;

L_{ha}: the length of the horizontal arc segment a, meter;

$\overline{v}$: the average pace of passengers in the horizontal transfer channel in the free flow state, m/s.

(2) Calculate the time cost of the vertical arc segment

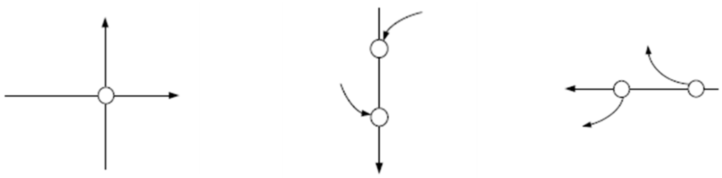
$$t_{va} = \frac{\delta \cdot L_{va}}{\eta \cdot \overline{v}} \tag{9}$$

t_{va}: the time cost of the vertical arc segment a, second;
L_{va}: the length of the vertical arc segment a, meter;
$\overline{v}$: the average pace of passengers in the horizontal transfer channel in the free flow state, m/s;
δ: conversion factor of the actual vertical walking distance relative to the length of the vertical arc segment;
η: conversion factor of the average pace of passengers in the horizontal channel relative to the vertical channel in a free flow state.
δ, η can be obtained through on-site investigation.

Time Cost of a Single Node

The time cost of a single node is the total delay caused by the change of passenger flow at a node. The main influencing factors include the form of flow line conflict at the node, the passenger flow on the flow line, and the congestion level of the flow line.

Since the delay time generated by the increase of the congestion level at the node was not considered when constructing the initial network of the transfer flow line, the impact of the conflict type on the delay time was mainly studied when calculating the time cost of the node. The types of conflicts between mutually vertical paths in the horizontal direction can be divided into three types: cross conflict, merging conflict and diversion conflict. The time cost is k_1, k_2, and k_3, as shown in Figure 5.



(**a**) (**b**) (**c**)

Figure 5. Schematic diagram of collision types. (**a**) cross conflict, (**b**) merging conflict, (**c**) diversion conflict.

(1) Determine the type of node conflict

Write a Java program to automatically identify the corresponding conflict type by calculating the relationship between two paths at the node. The specific steps are as follows:

Step 1: Remember that the number of the predecessor node of the flow k_1 into node v is a_1, and the number of the successor node is a_2. In the same way, remember that the number of the predecessor node where the flow k_2 into node v is b_1, and the number of the successor node is b_2. Starting from 1, the adjacent nodes of node v in the same plane are numbered counterclockwise from small to large integers until n, mark $a_1 = 1$, and the numbering rule is shown in Figure 6.

Step 2: if $a_1 = b_1$ and $a_2 = b_2$, no conflict occurs;

Step 3: if $a_1 = b_1$ and $a_2 \neq b_2$, it is a diversion conflict;

Step 4: if $a_1 \neq b_1$ and $a_2 = b_2$, it is a merging conflict;

Step 5: if $b_1 < a_2$ and ($b_2 > a_2$ or $b_2 = a_1$), flow k_1 and flow k_2 from its right form a cross conflict at node v, as shown in Figure 7;

Step 6: if $b_1 \geq a_2$ and $a_1 < b_2 < a_2$, flow k_1 and flow k_2 from its left form a cross conflict at node v, as shown in Figure 8.

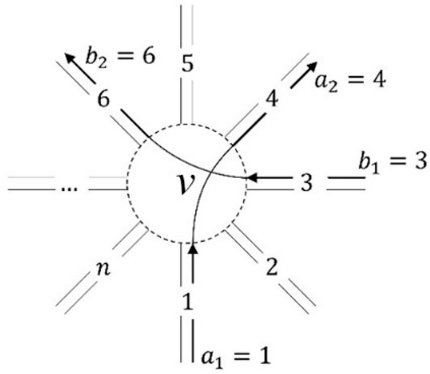


Figure 6. Schematic diagram of the node numbering rule.

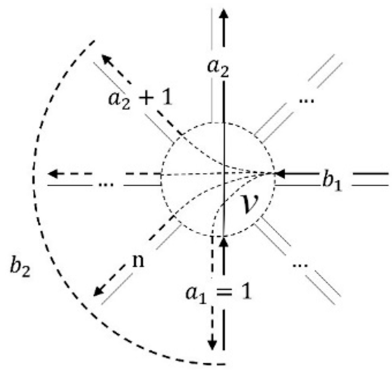


Figure 7. Schematic diagram 1 of cross collision path.

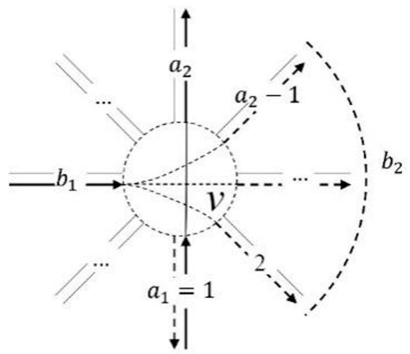


Figure 8. Schematic diagram 2 of cross collision path.

Therefore, after the n-th passenger flow distribution, the time cost b_v^n of the node is one of k_1, k_2, and k_3.

(2) Calculate the time cost of a single node

The existing time cost calculation methods mainly include the analytical method and simulation method. Given the relatively random behavior characteristics of passengers in the node area, it is more complicated to use the analytical method to calculate. The simulation method uses microscopic models to characterize passenger behavior and calculate related parameters.

This paper is based on a continuous social force model. It is assumed that passengers are subjected to various social forces such as squeezing force, friction force, repulsive force and attractive force during the transfer process. The transfer behavior is completed under various combined forces, using the Anylogic pedestrian simulation module in the software to analyze the delay level of passengers under three different conflict types. In the simulation, the passenger flow of a certain reference channel is fixed first, and the passenger flow of the other channel is gradually loaded from 0 until the node passenger flow is saturated, and then the passenger flow of the reference channel is gradually loaded, and the above steps are repeated. In this way, the delays of different types of conflicts and passenger flow of different channels are obtained, and the average delay of nodes caused by each type of conflict is calculated.

3.4. Program Design

3.4.1. Algorithm Flow

This paper writes a Java program, enters the three-dimensional coordinates of the start and end points of each transfer and the passenger flow between the start and end points, then it can generate the initial network of the transfer flow line and the set of transfer paths to be selected, and obtain the passenger flow of each node and arc segment. The program algorithm steps are as follows:

Step 1: Enter the name of each transfer start and end point, three-dimensional coordinates, and the passenger flow between the start and end points;

Step 2: According to the coordinates of the start and end points of the transfer, generate nodes and arc segments between the start and end points to construct a basic network;

Step 3: Perform clustering processing on all nodes to simplify the basic network;

Step 4: Let the initial value of the generalized impedance of the simplified basic network be $S_G^1 = B_G^0$;

Step 5: Calculate the total generalized impedance of each path between the start and end points, find the set of paths with the smallest total generalized impedance, calculate the total number of turns u_t in the set, eliminate the paths with the number of turns greater than $u_t^{\max}$, and evenly distribute the passenger flow from the start and end points to the remaining paths;

Step 6: Calculate the network time cost set B_G^n and the total transfer time cost $T(n)$ of the entire network time after this passenger flow distribution;

Step 7: Record the minimum value $T(n)_{\min}$ of the total transfer time cost of the entire network time after each distribution;

Step 8: If the number of distribution $n = n_{\max}$, terminate the program; Otherwise, recalculate the generalized impedance of the entire network from Equation (7), and return to Step 5.

3.4.2. Scheme Generation and Comparison

(1) Weight coefficient change

For each weighting coefficient $\lambda(0 \leq \lambda \leq 1)$, a transfer streamline network with $T(n)_{\min}$ when $T(n)$ is the minimum is generated, and the network can be further optimized by adjusting the value of λ. This paper adjusts with 0.01 as the step size and calculates the transfer streamline network when $T(n)$ is $\min\limits_{1 \leq n \leq n_{\max}, 0 \leq \lambda \leq 1} T(n)$ as the final plan. This paper finally selects the weight coefficient to be 0.67.

(2) Change of transfer start and end position

According to the priority of each transfer start and end candidate set, the next sequence start and the end position is selected, and a new transfer streamline network is generated and compared. Assuming that the candidate set of a transfer starting point has four candidate locations in order of priority, input the coordinates of each starting point in turn to generate the network, and compare the total time cost of different candidate points.

Through the above process, the layout of the pick-up and drop-off areas of the transportation modes within the hub can be optimized, and the overall optimization of the transfer flow network and the layout of each transportation mode can be realized.

4. Example Application

4.1. Determine the Transfer Start and End Location

This paper chooses the comprehensive passenger transport hub of Wuxi Station as an example to determine the starting and ending points of the transfer. The start and end numbers and layout of each mode of transportation are shown in Table 2 and Figure 9.

Table 2. List of transfer start and end point numbers of each transport mode at Wuxi station.

Transport Mode	Railway	Long-Distance Bus	Metro	Regular Bus	Suburban Bus	Taxi	Private Car
Serial number	A	B	C	D	E	F	G

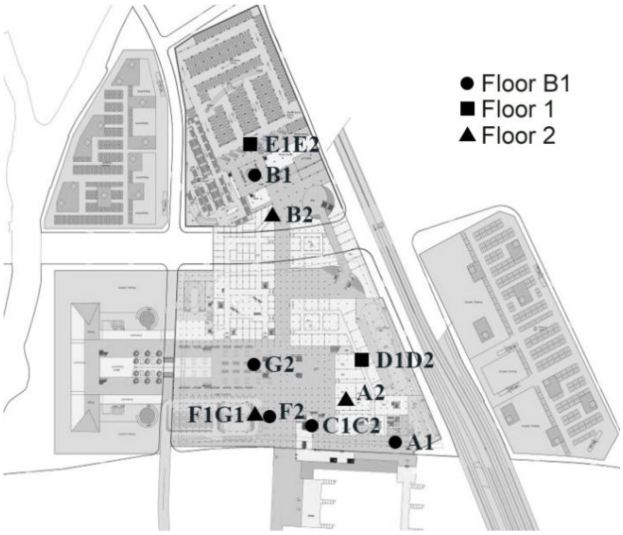


Figure 9. Layout of origin-destination points of each transport mode at Wuxi station.

4.2. Initial Network Generation for Transfer Flow Lines

According to the Wuxi Station Comprehensive Passenger Transport Hub Planning Plan (2020) and the post-traffic evaluation report, combined with actual survey data, the planned annual peak hour passenger flow is used as the passenger flow. The passenger flow transfer matrix between various transportation modes is shown in Table 3.

Table 3. Scheduled annual passenger change flow table of Wuxi station (Unit: person-time/hour).

Transport Mode	Railway	Metro	Long-Distance Bus	Suburban Bus	Regular Bus	Taxi	Private Car	Sum
Railway	0	2079	441	296	786	592	304	4498
Metro	2456	0	960	300	300	300	300	4616
Long-distance bus	386	974	0	0	384	281	153	2178
Suburban bus	293	300	0	0	0	0	0	593
Regular bus	878	300	384	0	0	0	0	1562
Taxi	649	250	0	0	0	0	0	899
Private car	354	300	0	0	0	0	0	654
Sum	5016	4203	1785	596	1470	1173	757	15,000

After entering the name, coordinates passenger flows of the start and end points of the transfer in the program. The program shows that when $\lambda = 0.65$ and the number of allocations $n = 207$, the optimal solution is obtained. The distribution state of the passenger flow is shown in Figure 10. The cross-sectional size of each channel in the figure is proportional to the flow of passengers.

The result of the transfer path selection between the transfer start and end points is shown in Figure 11.

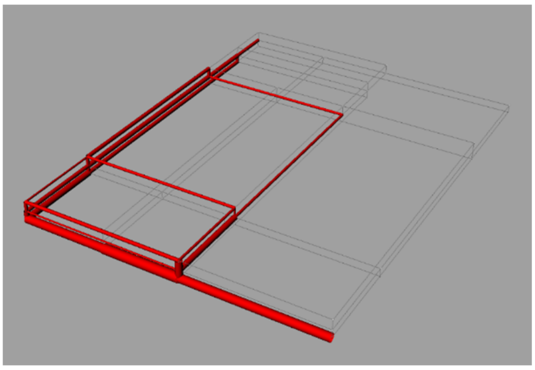
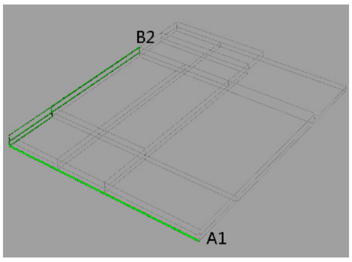
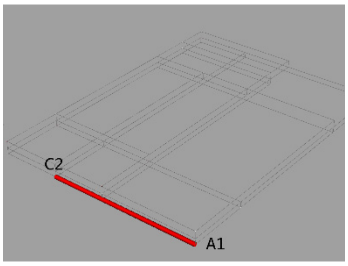


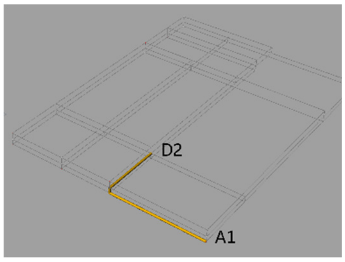
Figure 10. Initial network generation result of the transfer streamline of Wuxi station.



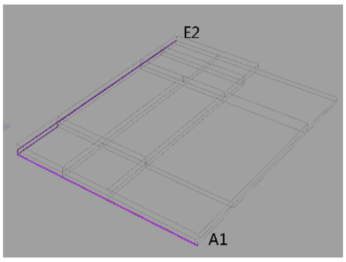
railway transfer to long-distance bus



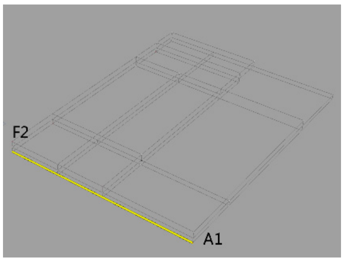
railway transfer to metro



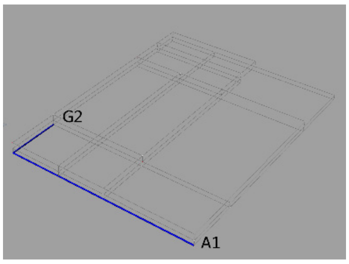
railway transfer to regular bus



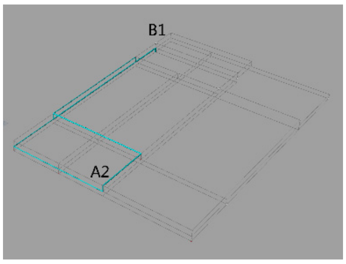
railway transfer to suburban bus



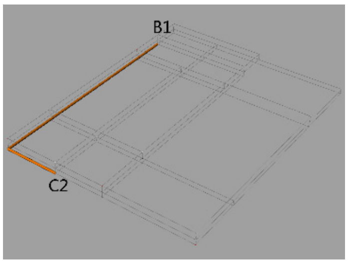
railway transfer to taxi



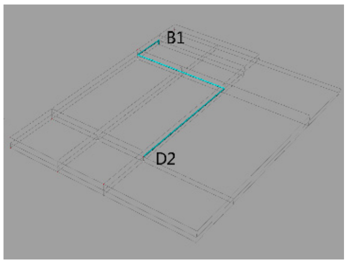
railway transfer to private car



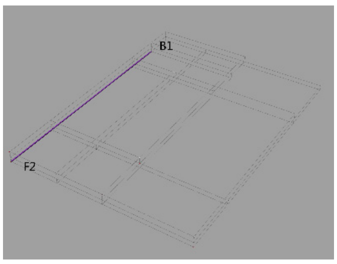
long-distance bus transfer to railway



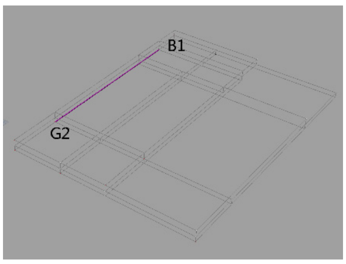
long-distance bus transfer to metro



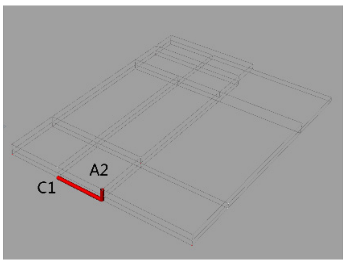
long-distance bus transfer to regular bus



long-distance bus transfer to taxi



long-distance bus transfer to private car



metro transfer to railway

Figure 11. *Cont*.

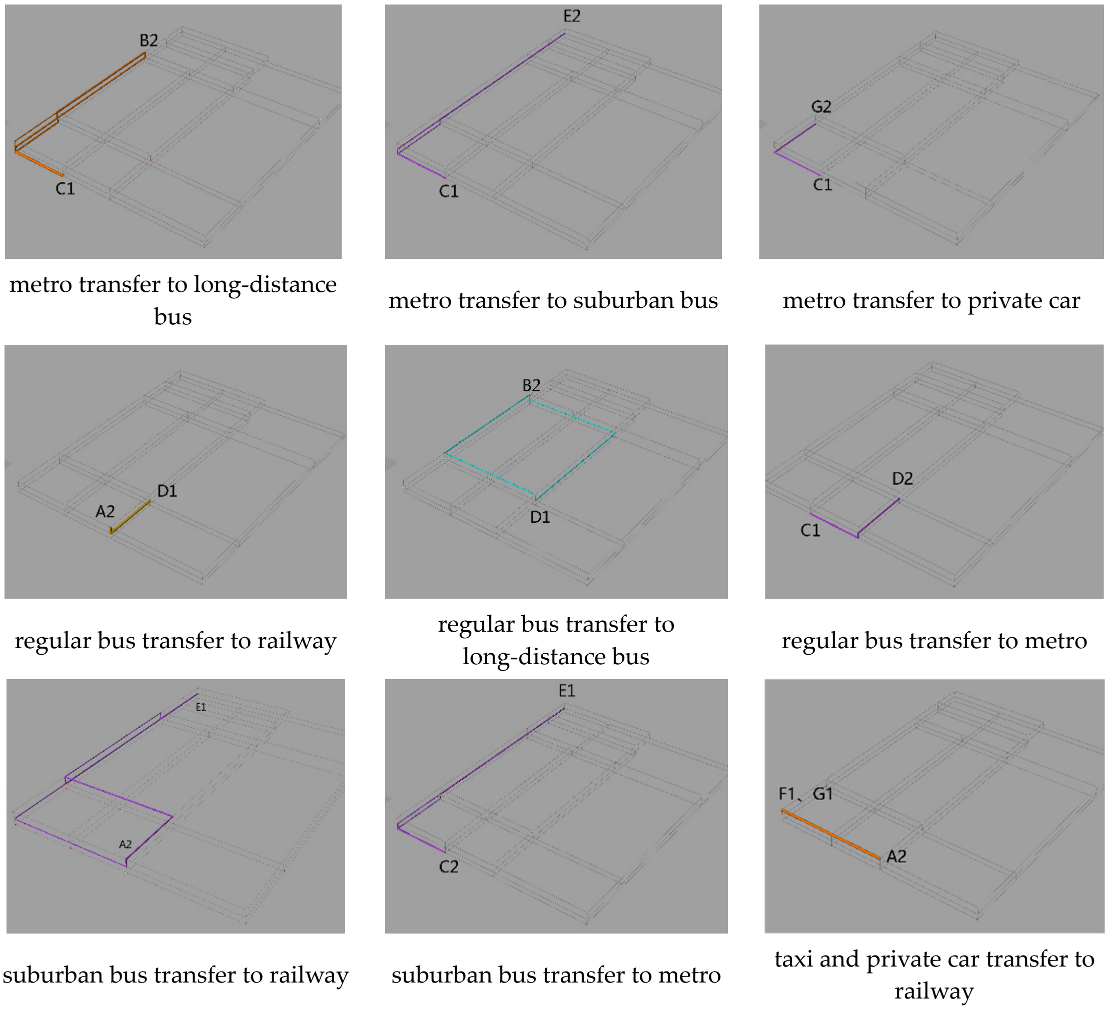


Figure 11. Results of transfer route generation for each mode of transportation.

By transforming the coordinates and parameters of the transfer start and end points, the initial network plan for the remaining transfer flow lines can be obtained, and the transfer efficiency of different plans can be determined by comparing the total time cost of the entire network.

4.3. Comparison of Optimization Results

Other streamline initial network schemes can be obtained by permuting the OD point coordinates and the variation of input parameters, and the full network. The total time cost value of the network can be used to compare the efficiency of each scheme, as shown in Table 4.

Table 4. Comparison table of optimization results.

Index	Current Transfer Time Per Person	Optimized Transfer TIME Per Person	Percentage of Transfer Time Optimization
Average transfer time (Second)	270	182	32.59%

As can be seen from Table 4, the weight coefficient used in this paper is 0.65. According to the calculation of 15,000 passengers changing flow at Wuxi Station, the model finally obtains the optimal solution T = 2,738,027 s, that is, the average transfer time per person after optimization is 3 min 2 s. Compared with the current survey data, the average transfer time per person being 4 min 30 s, the research results of this paper shorten the transfer time by 32.59%, thus the optimization effect is significant.

In summary, this chapter verifies the effectiveness and implementability of the method by taking the comprehensive railroad passenger hub in the North Square of Wuxi Station as a case study and conducting the interchange process analysis, the initial network design of interchange flow lines and its optimization and the layout of functional nodes of interchange flow lines in turn.

5. Conclusions

This paper analyzes the priority ranking of the transfer start and end layout factors of the transportation modes in the comprehensive passenger transport hub, so as to determine the start and end points of the transfer streamline network, and realize the coordinated layout between the hub transfer streamline and each transportation mode. Considering passenger transfer efficiency, the research analyzes passenger route selection factors, generates and simplifies the basic network of transfer streamlines. Based on the improved shortest path allocation algorithm, the passenger flow distribution of the transfer streamline basic network is carried out, and the algorithm program is established to realize the automatic generation of the transfer flow line initial network. The initial network plan of the transfer streamline is selected according to the comparison of the starting and ending candidates. When calculating the node time cost in the improved shortest path allocation algorithm, this paper takes the average delay of the highest conflict level of the node as a parameter.

In the future, we can further study the node delay of the coexistence of multiple node conflict types, so as to analyze the impedance function more finely. The main influencing factors determined in the transfer streamline of this paper are the number of turns and transfer time. The influencing factors of passenger transfer time can be further studied. In the future, on the basis of the streamline network, the layout of different functional nodes on each path could be carried out according to the flow analysis. The distribution map of the whole network could be obtained by merging the same adjacent functional nodes. The distribution map of functional nodes would reflect the layout and scale attributes of functional nodes. Different types of functional nodes in different modes of transportation could correspond to their unique facilities and equipment requirements.

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