Journal of Civil Engineering and Urban Planning (2023) **DOI: 10.23977/jceup.2023.050105**
Clausius Scientific Press, Canada **ISSN 2616-3969 Vol. 5 Num. 1**

Modeling and Simulation Analysis for Urban Rail Transit Hub

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Keywords: Urban rail transit hub, Agent-based modeling and simulation, Dynamic evaluation, Model performance, Distribution efficiency, Dynamic service level, Emergency capacity

Abstract: Urban rail transit has become the main mode to ease traffic congestion, and urban rail transit hub is the most important area for passenger flow distribution in urban rail transit system. Study on the method of simulation and dynamic evaluation of urban rail transit hub has an important significance for train scheduling, operation organization and risk prevention under the viewpoint of traffic safety and service level. This paper analyzed the system characteristics of urban rail transit hub, proposed agent-based modeling and simulation design, simulation process based on Anylogic, dynamic evaluation index set and classification criteria. Furthermore, Beijing South Subway Station was selected for case study, simulation models which included hub simulation model, passenger flow simulation model and train simulation model were built, and experiment results showed that simulation models had a good performance, which was accordant with the reality scene, simulation error was 0.027. Meanwhile, dynamic evaluation which included distribution efficiency, dynamic service level and emergency capacity during the operation period was researched, and optimizing suggestion was proposed, which could provide the beneficial reference for traffic managers.

1. Introduction

In recent years, urban rail transit has become the main mode to ease traffic congestion. Urban rail transit hub is the most important area for passenger flow distribution in urban rail transit system. Study on the method of simulation and dynamic evaluation of urban rail transit hub has an important significance for train scheduling, operation organization and risk prevention under the viewpoint of traffic safety and service level.

With regard to modeling and simulation of urban rail transit hub, the research purpose is to improve passenger traffic service quality and reliability. According to the hierarchy of modeling and simulation, passenger flow model contains macroscopic model, mesoscopic model and microscopic model. Early research mainly focused on the correlation among traffic flow, velocity and density, research findings represented by Fruin J. J. [1] were adopted as an effective macroscopic analysis approach for passenger traffic in the US Highway Capacity Manual. As the representative of mesoscopic model, lattice gas model was firstly proposed to passenger flow simulation by Muramatsu M., et al. [2]. With the rapid development of computer technology, microscopic model was proposed and applied to simulation, which mainly included magnetic model [3], benefit cost cellular model [4], queuing network model [5], social force model [6] and cellular automata model [7]. Helbing M. [8] proposed social force model to clarify the complex characteristic of passenger flow. Daamen W., et al. [9, 10] analyzed the interrelation between passenger path-finding behavior and interlayer facility layout, experiment results showed that passenger flow crowd degree of interlayer facility was the key factor affecting route choice behavior directly. Seriani S., et al. [11] explored the pedestrian traffic management of boarding and alighting in metro stations, obtained the management criteria of platform and metro doors by micro-simulator and laboratory experiments, results showed that service level, service time and passenger flow density could provide reference for pedestrian traffic management in metro systems. Schelenz T., et al. [12] proposed an agent-based simulation method for calculating passenger dwell time and analyzing passenger preferences with different vehicle layout designs, results proved that the number of vehicle doors had a direct effect on passenger dwell time. Zhang Q., et al. [13, 14] proposed a cellular automata-based alighting and boarding micro-simulation model, and a grid-based micro-simulation model for passengers in Beijing metro stations, simulation experiments with different alighting and boarding group sizes and ratios were developed for model verification, results indicated that efficiency evaluation of transfer stations should consider integrated effects of passenger flow volume, facility attributes and train timetable.

With regard to dynamic evaluation for urban rail transit hub, according to the evaluation requirement for the service level of urban rail transit hubs,Zhang Q. [15] proposed the evaluation index system and evaluation method based on simulation technology considering the interactive features of passenger and hub environment. Li W. [16] established a feasible evaluation index system for passenger transfer hub, and proposed the grey relationship multi-criteria appraising model to evaluate the service efficiency of urban passenger transfer hub. Sun L S. [17] present an evaluation method based on three optimization indexes which included comfort degree, advantage degree and harmony degree. Yang X G., et al. [18] analyzed the existing problems of traffic information service in urban rail transit hubs from the perspective of the passengers, and then proposed an approach for optimum design through the combination of static information and dynamic information, in order to realize the humanization and systematization of traffic information service in urban rail transit hubs. Li D W. [19] proposed a simulation evaluation model of microscopic pedestrian flow, and developed the simulation software named MTR-PedSIM. Furthermore, Shi D H. [20] analyzed the meaning of service quality of railway transportation systems, and then evaluated the service level of corresponding facility utilities considering railway loading, delay and restoration possibility. Based on the entropy and Topsis evaluation method, Shi F S. [21] discussed the application of mending ideal solution in the logistics planning of railway freight yards, established the evaluation index system on logistics service level of freight yards, and then studied on the comprehensive evaluation on the comprehensive logistics service level of three freight yards. Kuo. M. S., et al. [22] proposed an evaluation method of service level based on the integration between VIKOR and GRA under the fuzzy environment in airport.

From the above research, it could be found that kinds of models and methods were widely used to study on simulation and evaluation in urban rail transit hub. However, there were little research on the agent-based simulation and dynamic evaluation for urban rail transit hub under the viewpoint of traffic safety and service level. Therefore, the objective of this research is to develop a method for agent-based simulation and dynamic evaluation in urban rail transit hub. The anticipated achievement could enrich the theory system of urban rail transit hub, and provide the beneficial reference for traffic managers.

2. Agent-Based Modeling and Simulation Design

2.1 System Behavior Analysis of Urban Rail Transit Hub

The internal environment of urban rail transit hub has evolved into a rather complex service network system. System behavior of urban rail transit hub could be defined as the dynamic relationship of passenger flow between internal environment and external environment, and dynamic variation regulation of internal passenger flow. System behavior characteristics of urban rail transit hub are as follows.

(1) Passenger aggregation: interaction with different passenger aggregations is expressed as passenger flow movement, and the purpose of passenger aggregation is to achieve the transfer demand by using the internal facilities of urban rail transit hub and rail trains.

(2) Passenger flow: there is passenger flow exchange between the internal facilities of urban rail transit hub and rail trains.

(3) Nonlinear characteristic: the dynamic relationship of passenger flow between internal environment and external environment is expressed as nonlinear characteristic, and the dynamic variation regulation of internal passenger flow is also expressed as nonlinear characteristic.

Therefore, urban rail transit hub system could be defined as a typical complex adaptive system. And then, passenger aggregation in urban rail transit hub could be defined as the passenger agent set. Passenger agent characteristics of urban rail transit hub are as follows.

(1) Behavior boundary: passenger behavior is expressed with specific boundary and independent.

(2) Goal-oriented: passenger behavior is expressed with specific goal-oriented region.

(3) Partial information: passenger could adjust action plan based on the partial information in urban rail transit hub.

(4) Diverse attributes: there are diverse attributes for passenger agent, which include age, gender, weight, volume, expected velocity and object region.

2.2 Agent-Based Modeling and Simulation Design

On the basis of complex adaptive system theory, the method of agent-based modeling and simulation (ABMS) is developed for research on complex system by combining with computer simulation technology [23]. With connection rules, communication protocol and interactive mode among different agents, macro-model of complex system is built, meanwhile, system behavior could be analyzed by using computer simulation platform. Macal C M. and North M J. [24] systematically present the method of ABMS for complex system. Based on the research findings above, agent-based modeling and simulation design is developed in this paper, which is shown in Figure 1.

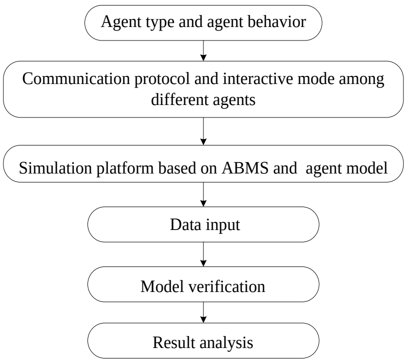


Figure 1: Schematic Diagram of Agent-Based Modeling and Simulation Design

Combining with the system behavior analysis and passenger agent characteristics, in this paper, passenger agent model based on belief-desire-intention (BDI) is proposed, which could express independent traffic behavior of passenger in the virtual environment of hub system [25,26]. Passenger agent model based on BDI includes behavior sensor, knowledge database, decision-making processor and behavior generator. The structure of passenger agent model based on BDI is shown in Figure 2.

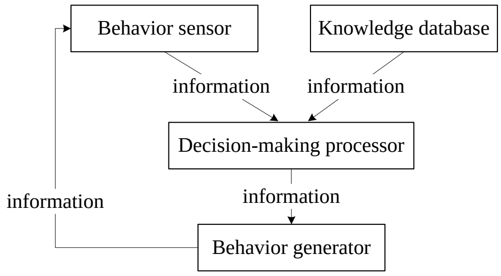


Figure 2: Structure Diagram of Passenger Agent Model Based on Bdi

Simulation platform based on ABMS could provide simulation environment and simulation parameters for passenger agent, meanwhile, it could provide intermediary for communication and cooperation among multiple agents. Based on the characteristic and function of agent, the agents in simulation environment of urban rail transit hub could be divided into three types, which are hub facility agent, rail train agent and passenger agent. Hub facility agent reflects the simulation environment, structure attribute and function attribute of hub facility. Rail train agent reflects service attribute of rail train. Furthermore, hub facility agent and rail train agent collectively reflect the boundary of simulation environment.

2.3 Simulation Platform and Core Algorithm

Anylogic is a professional simulation environment for virtual prototyping based on UML-RT, Java and differential equation. It is efficiently used for the simulation of complex systems which contain discrete system, continuous system and hybrid system [27, 28, 29]. So far, Anylogic is widely applied to the dynamic simulation in traffic. In this research, Anylogic 7.3.6 Professional Edition is selected as simulation platform. And then, based on the parameters of hub structure and facility layout, simulation model of hub facility agent could be developed; the simulation models of rail train agent and passenger agent could be developed by Pedestrian Library and Rail Library in Anylogic.

Social force model indicates that the forces of the moving passenger include self-drive force, the repulsion between passengers, and the repulsion between passenger and barrier. And then, the basic dynamic equation of social force model is shown as follows.

$$m_i \frac{\mathrm{d}v_i}{\mathrm{d}t} = f_i + \sum_{j \neq i} f_{ij} + \sum_{w} f_{iw} \tag{1}$$

Where, m_i refers to the mass of passenger i; $\mathrm{d}v_i/\mathrm{d}t$ refers to the acceleration of passenger i at time t; f_i refers to self-drive force of passenger i; f_{ij} refers to the repulsion between passenger i and passenger j; f_{iw} refers to the repulsion between passenger i and barrier w.

$$f_i = m_i \frac{v_i^0(t) \cdot \vec{\mathbf{e}}_i^0(t) - \vec{\mathbf{v}}_i(t)}{\tau_i} \tag{2}$$

Where, $v_i^0(t)$ refers to the scalar of expected velocity of passenger i at time t; $\vec{\mathbf{e}}_i^0(t)$ refers to the direction vector of unit expected velocity of passenger i at time t; $\vec{v}_i(t)$ refers to the vector of actual velocity of passenger i at time t; τ_i refers to the relaxation time from actual velocity to expected velocity for passenger i.

$$f_{ij} = [A_i \cdot \exp(\frac{r_{ij} - d_{ij}}{B_i}) + k \cdot G(r_{ij} - d_{ij})] \cdot \vec{n}_{ij} + \mu \cdot G(r_{ij} - d_{ij}) \cdot \Delta v_{ij}^t \cdot t_{ij} \quad (3)$$

Where, A_i refers to the strength parameter of repulsive between passenger i and passenger j; B_i refers to the distance parameter of repulsive between passenger i and passenger j; r_{ij} refers to the sum of radius of passenger i and passenger j; d_{ij} refers to the center distance between passenger i and passenger j; k refers to the elasticity coefficient of passenger i when passenger i is in touch with passenger j or barrier w; $G(\bullet)$ refers to the Bool function, $G(\bullet)=1$ if passenger i is in touch with passenger j or barrier w, otherwise, $G(\bullet)=0$; $\vec{n}_{ij}$ refers to the unit direction vector from passenger i to passenger j; μ refers to the friction coefficient of passenger i when passenger i is in touch with passenger j or barrier w; Δv_{ij}^t refers to the difference value of velocity scalar between passenger i and passenger j at time t; t_{ij} refers to the relaxation time from no-touching to touching between passenger i and j.

$$f_{iw} = [A_w \cdot \exp(\frac{r_i - d_{iw}}{B_w}) + k \cdot G(r_i - d_{iw})] \cdot \vec{n}_{iw} + \mu \cdot G(r_i - d_{iw}) \cdot v_i^t \cdot t_{iw} \quad (4)$$

Where, A_w refers to the strength parameter of repulsive between passenger i and barrier w; B_w refers to the distance parameter of repulsive between passenger i and barrier w; r_i refers to the radius of passenger i; d_{iw} refers to the center distance between passenger i and barrier w; $\vec{n}_{iw}$ refers to the unit direction vector from passenger i to barrier w; v_i^t refers to the velocity scalar of passenger i at time t; t_{iw} refers to the relaxation time from no-touching to touching between passenger i and barrier w.

With regard to the parameter of social force model, Jia H F. [30] provides the parameter values based on passenger data in Xi-Zhimen subway station, which are list in Table 1.

Table 1 Parameter values of social force model

Parameter	Value	Unit
A_i	2.57	m^2/s^2
A_w	$-m_i v_i^0 / \tau_i$	m^2/s^2
B_i	0.2	m
B_w	0.5	m
k	$1.2*10^5$	kg/s^2
m_i	70	kg
r_{ij}	0.6	m
v_i^0	1.39	m/s
μ	$2.4*10^5$	kg/s^2
τ_i	0.5	s

Based on the research above, it could be concluded that social force model is able to reflect passenger intention, and the interaction among different passengers or barriers. It has become the most applied method for study on the pedestrian dynamics in urban rail transit hub.

2.4 Simulation Process Design

In this paper, simulation process design by Anylogic is proposed, which includes simulation model design, parameter setting, simulation operating and result analysis. Simulation process design by Anylogic is shown in Figure. 3.

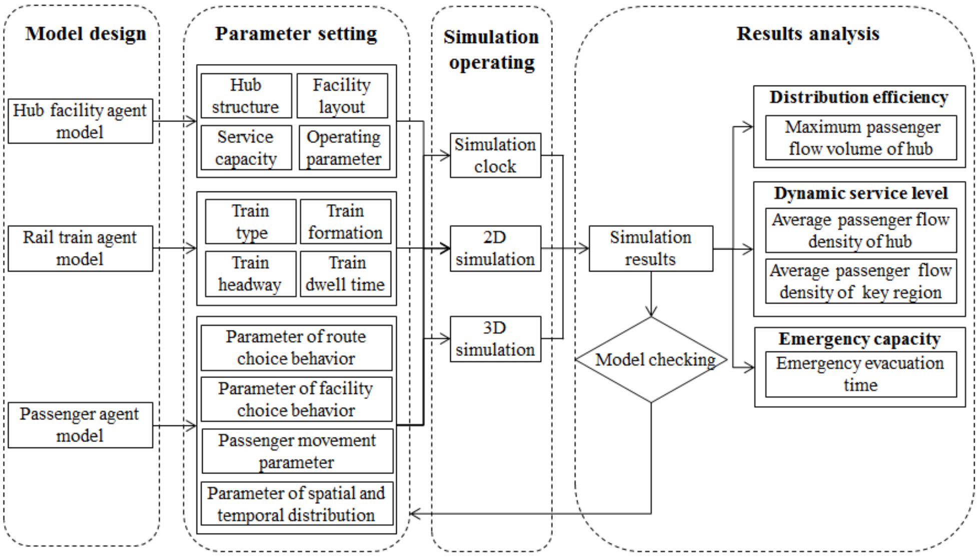


Figure 3: Simulation Process Design by Anylogic

3. Dynamic Evaluation Index Set and Classification Criteria

In this paper, with regard to the study on dynamic evaluation of urban rail transit hub, evaluation objects which include hub distribution efficiency, dynamic service level and emergency capacity are proposed. Furthermore, the evaluation index and classification criteria for each evaluation object are built, which are shown in Table 2. The corresponding classification criteria for distribution efficiency or dynamic service level is derived from the code for design of railway passenger station buildings [31]; The corresponding classification criteria for emergency capacity is derived from the code for design for metro [32].

Table 2 Dynamic evaluation index and classification criteria of urban rail transit hub

Evaluation object	Evaluation index	Symbol	Classification criteria					Unit
			A	B	C	D	E	
Distribution efficiency	Maximum passenger flow volume of hub	I_1	>10000	6000-10000	3000-6000	600-3000	<600	*p*
Dynamic service level	Average passenger flow density of hub	I_2	<0.25	0.25-0.70	0.70-1.15	1.15-2.0	>2.0	p/m^2
	Average passenger flow density of key region	I_3	<0.83	0.83-1.28	1.28-2.78	2.78-6.67	>6.67	p/m^2
Emergency capacity	Emergency evacuation time	I_4	<360					*s*

4. Case Study

4.1 Case Scenario

As a typical urban rail transit hub, Beijing South Subway Station (BSSS) contains subway line 4 and line 14, which is located in the underground of Beijing South Railway Station. It is convenient for passenger transfer among the different traffic modes such as high-speed railway, urban rail transit and urban public bus. In this paper, Beijing South Subway Station is selected for case study, and the practical investigation date is from June 6 to June 12, 2016.

4.2 Results Analysis

(1) Model performance

With regard to the hourly average passenger flow volume of hub, average absolute relative error (AARE) between numerical simulation and actual statistic is calculated for simulation precision verification. The calculation results of simulation precision are list in Table 3.

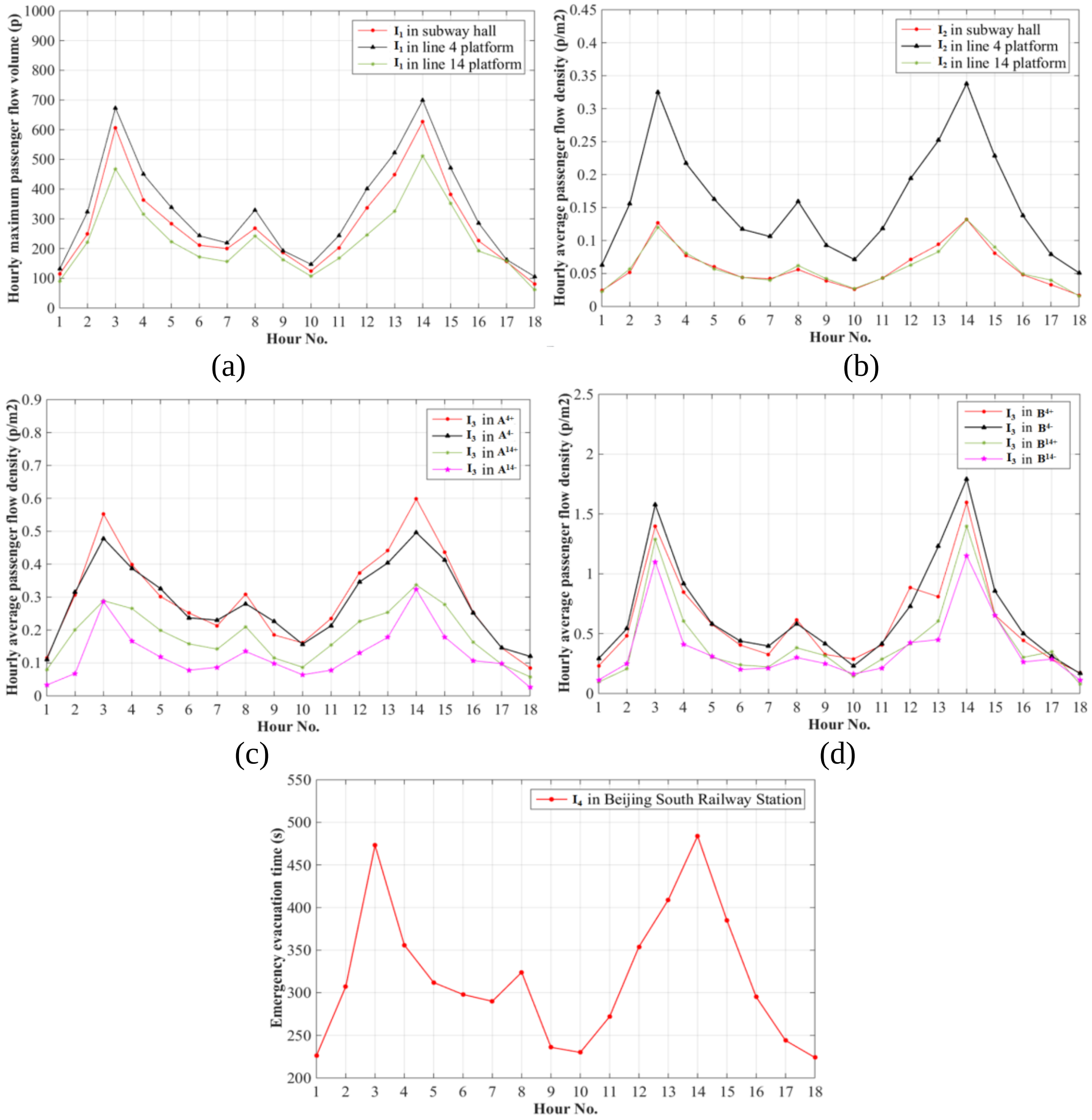
Table 3 Calculation results of simulation precision

No.	Hourly period	Hourly average passenger flow volume of hub (*p*)		AARE
		Numerical simulation	Actual statistic	
1	05:30-06:30	286	281	0.018
2	06:30-07:30	675	699	0.034
3	07:30-08:30	1485	1530	0.029
4	08:30-09:30	960	957	0.003
5	09:30-10:30	718	721	0.004
6	10:30-11:30	532	523	0.017
7	11:30-12:30	489	505	0.032
8	12:30-13:30	714	729	0.021
9	13:30-14:30	461	483	0.046
10	14:30-15:30	321	316	0.016
11	15:30-16:30	522	549	0.049
12	16:30-17:30	836	833	0.004
13	17:30-18:30	1102	1159	0.049
14	18:30-19:30	1562	1546	0.010
15	19:30-20:30	1025	1052	0.026
16	20:30-21:30	598	593	0.008
17	21:30-22:30	405	430	0.058
18	22:30-23:30	211	224	0.058
Average value of AARE				0.027

From Table 3, it could be indicated that the average value of AARE between numerical simulation and actual statistic is 0.027. That means the agent-based simulation model has a good performance, which should be accordant with the reality scene.

(2) Calculation results of evaluation indexes

Based on the practical investigation, this paper sets eight key regions in Beijing South Subway Station, which refer to the waiting areas of platforms and the entrance/exit areas of interlayer facilities. The waiting areas of platforms include waiting area of line 4 platform to up-direction (A^{4+}), waiting area of line 4 platform to down-direction (A^{4-}), waiting area of line 14 platform to up-direction (A^{14+}) and waiting area of line 14 platform to down-direction (A^{14-}). The entrance/exit areas of interlayer facilities include entrance area of interlayer facility between subway hall and line 4 platform (B^{4+}), exit area of interlayer facility between subway hall and line 4 platform (B^{4-}), entrance area of interlayer facility between subway hall and line 14 platform (B^{14+}) and exit area of interlayer facility between subway hall and line 14 platform (B^{14-}). And then, the calculation results of evaluation indexes during the daily operation period are shown in Figure 4.



(e)

(a) I_1 in BSSS, (b) I_2 in BSSS, (c) I_3 in the waiting areas of platforms, (d) I_3 in the entrance/exit areas of interlayer facilities, (e) I_4 in BSSS

Figure 4: Calculation Results of Evaluation Indexes in Bsss during the Daily Operation Period

From Figure 4, it could be indicated that hourly passenger flow volume presents a dynamic variation tendency in BSSS during the daily operation period, which has the clear tidal phenomena and peak valley phenomenon.

(3) Dynamic evaluation results

Based on the calculation results of evaluation indexes during the daily operation period in Figure 4 and the classification criteria in Table 2, dynamic evaluation results of distribution efficiency in BSSS during the daily operation period is shown in Figure 5; dynamic evaluation results of dynamic service level in BSSS during the daily operation period is shown in Figure 6; dynamic evaluation results of dynamic service level in the waiting areas of platforms during the daily operation period is shown in Figure 7; dynamic evaluation results of dynamic service level in entrance/exit areas of interlayer facilities during the daily operation period is shown in Figure 8.

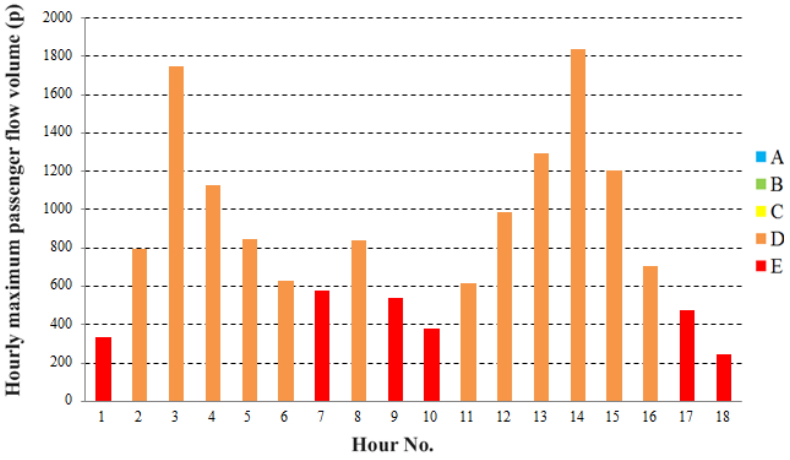


Figure 5: Dynamic Evaluation Results of Distribution Efficiency in Bsss during the Daily Operation Period

From Figure 5, it could be indicated that the distribution efficiency in BSSS during the daily operation period is in the level D or level E. That means there is still plenty of residual capacity for passenger distribution and transfer.

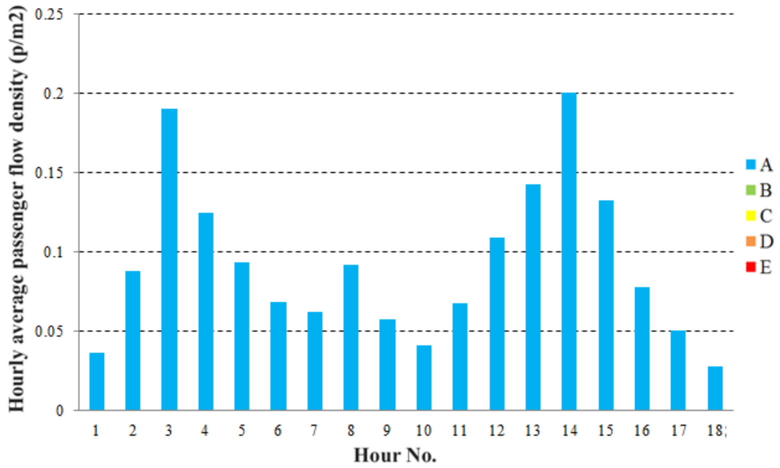
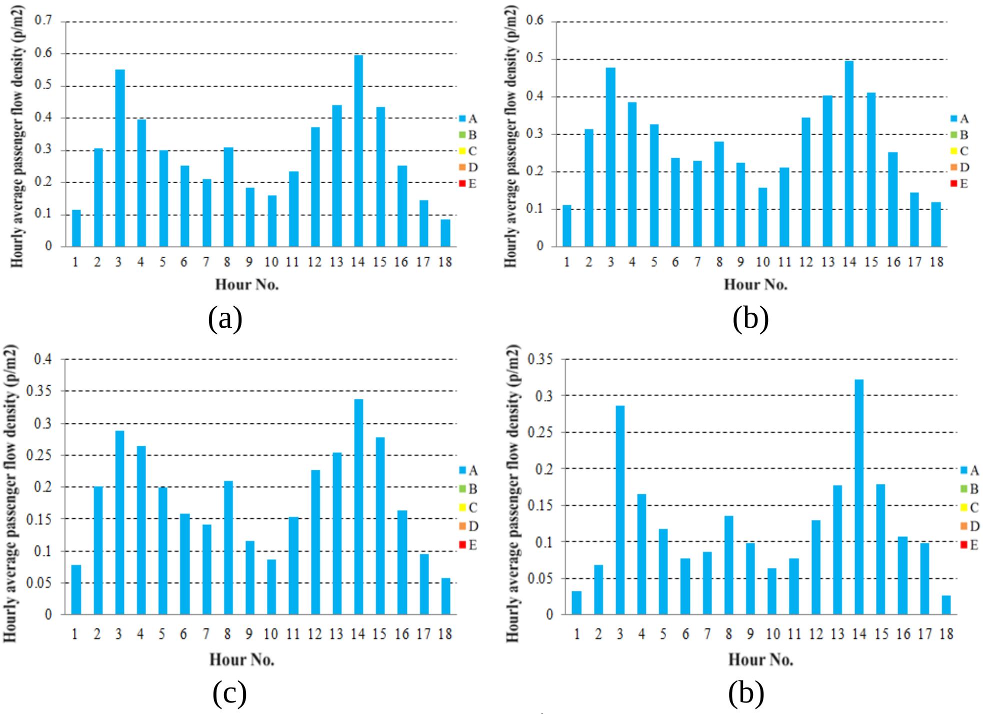


Figure 6: Dynamic Evaluation Results of Dynamic Service Level in Bsss during the Daily Operation Period

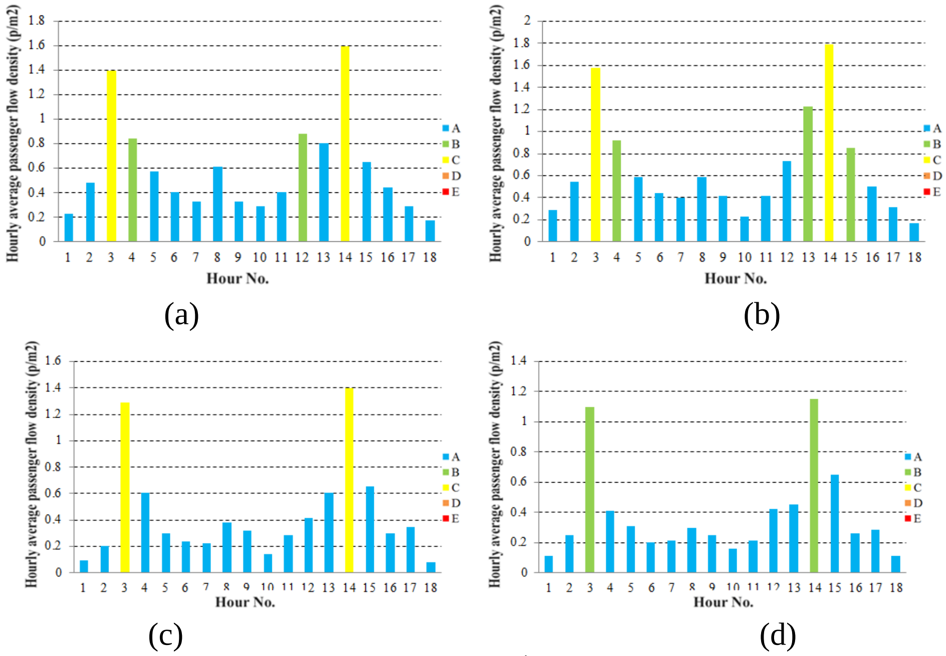
From Figure 6, it could be indicated that the dynamic service level in BSSS during the daily operation period is in the level A. That means the dynamic service level is comparatively ideal, the overall passenger flow state is free-flow, the congestion degree of passenger flow is comparatively low.

From Figure 7, it could be indicated that the dynamic service level in the waiting areas of platforms during the daily operation period is in the level A, which is similar to the results in Figure 7. That means the dynamic service level in the waiting areas of platforms is comparatively ideal, the corresponding passenger flow state is free-flow, the congestion degree of passenger flow in these key regions is comparatively low.



(a) Dynamic evaluation results of service level in A^{4+}, (b) Dynamic evaluation results of service level in A^{4-}, (c) Dynamic evaluation results of service level in A^{14+}, (d) Dynamic evaluation results of service level in A^{14-}

Figure 7: Dynamic Evaluation Results of Dynamic Service Level in the Waiting Areas of Platforms during the Daily Operation Period



(a) Dynamic evaluation results of service level in B^{4+}, (b) Dynamic evaluation results of service level in B^{4-}, (c) Dynamic evaluation results of service level in B^{14+}, (d) Dynamic evaluation results of service level in B^{14-}

Figure 8: Dynamic Evaluation Results of Dynamic Service Level in the Entrance/Exit Areas of Interlayer Facilities during the Daily Operation Period

From Figure 8, it could be indicated that the dynamic service level in the entrance/exit areas of interlayer facilities presents a dynamic variation tendency. During the rush hour 07:30-08:30 and rush hour 18:30-19:30, the dynamic service level in these key regions is comparatively low.

(4) Optimizing suggestion

Based on the dynamic evaluation results above, it could be indicated that hourly passenger flow volume in line 4 platform is greater than the corresponding value in subway hall and line 14 platform. In further study, more experiments could be developed with different train headways and time lags, which could provide a beneficial reference for train scheduling and traffic managers.

5. Conclusion

Study on the method of simulation and dynamic evaluation of urban rail transit hub has an important significance for train scheduling, operation organization and risk prevention under the viewpoint of traffic safety and service level. Based on the system behavior analysis of urban rail transit hub, the agent-based modeling and simulation design was built. And then, simulation process based on Anylogic, dynamic evaluation index set and classification criteria were proposed. Furthermore, Beijing South subway station was selected for case study, experiment result showed that simulation models had a good performance, which was accordant with the reality scene. Meanwhile, dynamic evaluation results during the daily operation period were calculated, the optimizing suggestion with different train headways and time lags was proposed, which could provide a beneficial reference for train scheduling and traffic managers.

Acknowledgements

Authors gratefully acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 71974043).

Author Contributions: This research is not free of mistakes and inconveniences. All authors collaborated on the interpretation of the results and on the preparation of the manuscript.

Conflict of Interest: The authors declare no conflict of interest.

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