E3S Web of Conferences **535**, 04006 (2024) https://doi.org/10.1051/e3sconf/202453504006
ESCM-2024

Simulation modeling as a means of forecasting passenger traffic at Moscow Metro transfer stations

Galina Boikova[1,*] and *Pavel* Mironov[2]

[1]Moscow Polytechnic University, Moscow, Russia
[2]Moscow Aviation Institute (National Research University), Moscow, Russia

Abstract. The article substantiates the necessity of simulation modeling for passenger traffic processes at Moscow Metro stations. The study aims to develop a simulation model based on pedestrian flows to predict changes in their density and directions in the organization of the station space. The use of the method of structural analysis allowed to establish all the key objects of the studied processes and the links between them. Input parameters and process interaction rules are obtained using abstraction, synthesis, grouping, and statistical analysis techniques. Based on the results obtained, formal models of the behavior of each group of objects have been developed. A 3D twin model corresponding to the real research object was created to visualize the simulation model results and demonstrate the results of the scenario implementation. Moscow Metropolitan can use the results obtained for the operational management of flows at the stations and the modernization of their infrastructure.

1 Introduction

The transport system is a component of urbanized territories and refers to dynamic systems in which parameters and characteristics change continuously in time following the needs of the population and different sectors of the economy [1]. Researchers of such systems note that it is impossible to fully establish cause-and-effect relationships of all objects and processes, so the behavior of only its components should be distinguished and analyzed [1, 2].

Subway is at the heart of Moscow's transportation system. The system of Moscow metro lines connects most districts of the capital, and the ground public transportation system provides passenger transportation from or to areas remote from metro stations. According to statistical data, about 50% of passenger transportation in Moscow is carried by the metro [Moscow Metro: https://mosmetro.ru]. It should be noted that the number of passengers depends on the time of day and day of the week. Thus, passenger traffic, regardless of station, increases during weekday morning and evening peak hours. Seasonal changes in passenger traffic density are possible (e.g., due to vacation season, vacations).

[*] Co rresponding author: boykovagv@mail.ru

Certain conditions need to be created for the comfortable and safe movement of passengers at Moscow Metro facilities. In most cases, it is the organization and management of pedestrian flows on platforms, lobbies, escalators, and stairs. This may involve using a navigation system (floor, ceiling, wall) and the physical restriction or separation of pedestrian flows by specialized means (e.g., barriers). It should be considered that pedestrian flows are dynamic with changing characteristics depending on various conditions (e.g., train intervals, number of escalators operating in one direction, surface public transportation schedules).

Simulation methods are used to obtain a digital twin of the corresponding system to predict the behavior of such dynamic systems or their objects [3]. With its help, it is possible to process data to reproduce the processes of a real object in a computer environment.

Thus, *the study aims to* create a simulation model of pedestrian processes of the transfer hub in the Moscow Metro.

The main tasks of the study include obtaining a list of objects of the relevant processes with a description of their characteristics, formalizing models of the behavior of the established objects, and modeling the behavior of objects in a simulation model under certain conditions with the interpretation of the obtained results.

The study's theoretical significance lies in the formal description of the behavior of the objects of the system with the establishment of cause-and-effect relations of this behavior and obtaining appropriate models.

The practical significance of the study lies in using the obtained results to develop concepts of route organization when carrying out repair works on the modernization of Moscow Metro facilities and adjacent territories to the lobbies.

2 Materials and methods

The object of the study is pedestrian flows occurring at the Moscow Metro stations Ploshchad Ilyicha and Rimskaya.

Creating a digital twin of a subject area requires a detailed description of all key objects involved in its processes [4, 5]. This required the step-by-step (with a certain level of abstraction) establishment of parameters for interacting objects within existing processes. For this purpose, the *structural analysis method* was used. As researchers note in their works, the structural analysis method provides a list of all objects and their characteristics to formally describe the problem domain [4, 6, 7].

In addition to the list of problem area objects, it is required to establish all their qualitative and quantitative characteristics. For this purpose, *synthesis*, *abstraction*, *grouping,* and *statistical analysis methods* were used. The obtained results became the input parameters of the simulation model. Several studies have used this approach to create simulation models in different fields [8, 9].

In addition to the input parameters, it is required to establish the features of their realization to realize the processes in the simulation model [5, 9, 10]. This means that it is required to form rules for each process's occurrence, realization, and termination. Thanks to this approach, it is possible to establish the internal relations of the system, but also the degree and nature of the influence of external influences on them [6, 11, 12]. For this purpose, the study used *parametric modeling* and *graph theory* methods. Formal models were created to visualize and describe the results using the *graphical method*.

Simulation modeling methods were used to create a digital twin of the real pedestrian flow system of the research object. They are based on the *agent-based modeling* methodology. According to such a methodology, all the results obtained should be transformed into entities with autonomous behavior and can decide according to some set of rules and influence the environment [3, 5, 7].

The resulting model became the basis for implementing different scenarios of site behavior according to the developed concepts of infrastructure changes or pedestrian flow patterns.

3 Results

Rimskaya and Ploshchad Ilyicha metro stations are in the Tagansky District of the Central Administrative District of Moscow. A passage connects them. The stations are deep and have one island platform of pylon (Ploshchad Ilyicha) and column (Rimskaya) types. Each station has one exit located in a common underground pedestrian passage under Rogozhskaya Zastava Square. Figure 1 shows the connectivity graph of exits to the city from the stations.

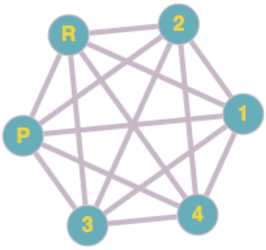

Fig. 1. Graph of connectivity of exits to the city from Ploshchad Ilyicha (P) and Rimskaya (R) stations.

In Figure 1, the numbers indicate exits to the city, which correspond to the accepted codification on the schemes of the Moscow Metro, namely:

- 1 – to the Moscow Central Diameter Serp and Molot station,
- 2 – to Rogozhskaya Zastava Square,
- 3 – to Sergia Radonezhskogo Street,
- 4 – to Zolotorozhsky Val Street.

This transportation hub is convenient for the passenger, allowing from any surface entrance to stations with two different metro lines. It should be noted that the stations are not overloaded. Figure 2 shows the statistics of passengers entering and exiting the stations.

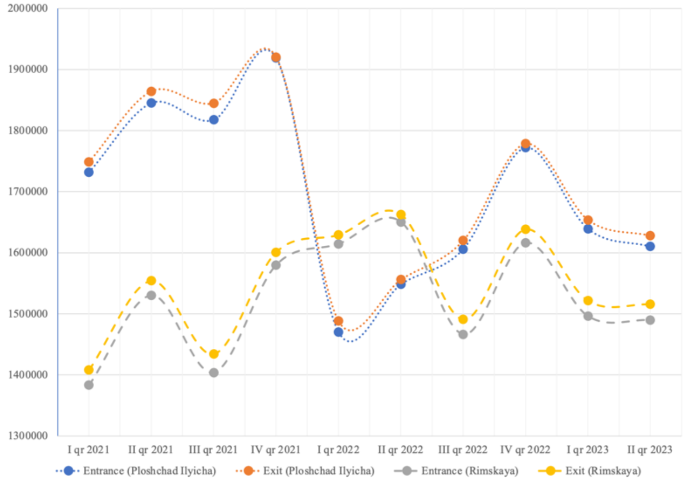

Fig. 2. Statistics of passengers entering and exiting Ploshchad Ilyicha and Rimskaya stations (compiled according to the Moscow City Government's open data portal: https://data.mos.ru).

Analyzing the statistical data, we can conclude that the stations are predominantly used:

- residents of neighborhoods for whom these stations are within walking distance;
- residents for whom it is convenient to reach the stations by ground public transportation (including residents of the Moscow region by suburban electric trains)
- workers who have workplaces located in nearby business centers or other facilities.

This conclusion can be drawn because of the insignificant variation in the number of passengers entering and exiting any station. This indicates that a passenger who has left the station is more likely to return to it upon completion of his personal (work) business due to the lack of an alternative route or its inconvenience.

The sharp drop in the level of passenger passage at Ploshchad Ilyicha station can be attributed to the start of construction works to prepare for the commissioning of the Moscow Central Diameter and changes in the routes of public transport bringing passengers to metro stations.

Many passengers use passage between stations – this was shown by observation data and statistical data analysis on passenger traffic at other stations on the same line. The number of passengers getting off the subway at other stations on the same line increases significantly. All this determines the need to manage pedestrian flows and organize the location of infrastructure so as not to "break" the flow.

Figure 3 shows the graph of pedestrian flows at the stations. At each station, there are two railroad tracks respectively a passenger can arrive or board a train at Rimskaya station at points R1 or R2 (in this case, the direction of the train does not matter), respectively for Ploshchad Ilyicha station – P1 and P2.

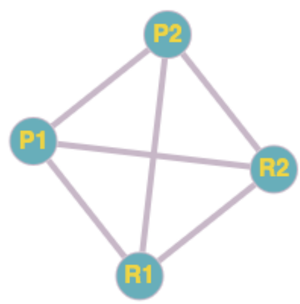

Fig. 3. Connectivity graph of passenger arrival and departure points.

Let us define the following routes (M_x) of passenger traffic inside the stations:

1. The passenger changes the direction of the train, i.e., changes from one track to another:
   - at the Ilyich Square station: M_1 = {P1, P2};
   - at the Rimskaya Square station: M_2 = {R1, R2}.
2. The passenger moves between the lines:
   - M_3 = {P1, R2};
   - M_4 = {P1, R1};
   - M_5 = {P2, R2};
   - M_6 = {P2, R1}.

The lines are traveled by eight-car trains, each with four doors. We assume that the micro-flows formed by the exit of passengers from each door unite into one common flow at a certain point of the platform. After that, the flow moves in a certain direction depending on the purpose: going out into the city or to another station. In this case, there may be slight deviations of individual passengers from the main flow, but in front of certain objects, the flow is still united (for example, at escalators to ascend or descend; at stairwells in the passage between stations).

Let us make a general parametric model of the routes, considering exits to the city and passenger movement within stations, by combining the graphs of Figure 1 and Figure 3:

1. For the Ilyich Square station:
- M_7 = {1, P1}; M_8 = {1, P2};
- M_9 = {2, P1}; M_{10} = {2, P2};
- M_{11} = {3, P1}; M_{12} = {3, P2};
- M_{13} = {4, P1}; M_{14} = {4, P2}.

2. For Rimskaya station:
- M_{15} = {1, R1}; M_{16} = {1, R2};
- M_{17} = {2, R1}; M_{18} = {2, R2};
- M_{19} = {3, R1}; M_{20} = {3, R2};
- M_{21} = {4, R1}; M_{22} = {4, R2}.

3. Mixed routes are possible for passengers via the intermediate Ploshchad Ilyicha station who are not familiar with the surface exit system:
- M_{23} = {1, R1, P}; M_{24} = {1, R2, P};
- M_{25} = {2, R1, P}; M_{26} = {2, R2, P};
- M_{27} = {3, R1, P}; M_{28} = {3, R2, P};
- M_{29} = {4, R1, P}; M_{30} = {4, R2, P}.

4. Mixed routes are possible for passengers via the intermediate Ploshchad Ilyicha station who are not familiar with the surface exit system:
- M_{31} = {1, P1, R}; M_{32} = {1, P2, R};
- M_{33} = {2, P1, R}; M_{34} = {2, P2, R};
- M_{35} = {3, P1, R}; M_{36} = {3, P2, R};
- M_{37} = {4, P1, R}; M_{38} = {4, P2, R}.

Based on this, models of pedestrian behavior were developed. Figure 4 shows a state diagram for a passenger who gets to the platform of one of the stations from an underground passage.

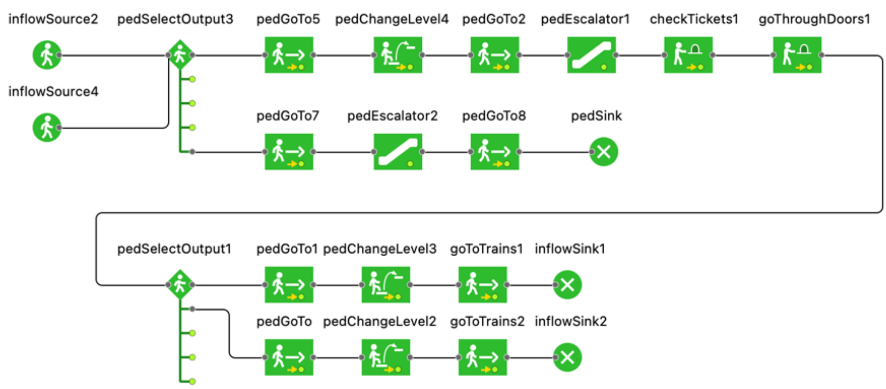

Fig. 4. Model of passenger behavior when a passenger enters the station from a crossing.

Figure 5 shows fragments of the simulation model in 3D format. For this purpose, simplifications have been made in the model that reduce the load on the computer's processing power (e.g., interior design). This does not affect the nature of pedestrian flows at the stations.

Let us present the results of one of the scenarios of pedestrian flow organization. There are no barriers to delineate the oncoming flows in the scenario of pedestrian movement across the platform to the escalators leading to the exit and to the escalators leading to the other station. Figure 6 shows the pedestrian traffic density map.

Fig. 5. 3D visualization of the simulation model fragment (station lobby and its platform).

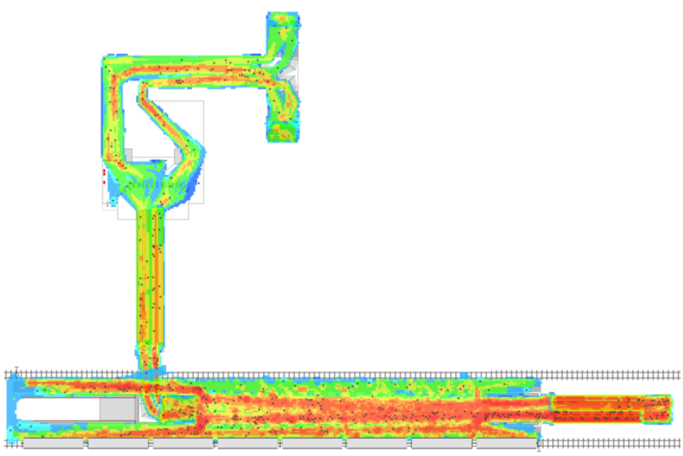

Fig. 6. Prediction map of passenger traffic density at the station in the simulation model.

Analyzing the obtained results, we can conclude that, in this case, there is a hindrance of traffic in the oncoming pedestrian flow near the escalators. This can be justified because many people congregate at the escalator on the way up and begin to collide with pedestrians on the way down.

4 Discussion

As a result of using the structural analysis method, a formal description of the problem domain with a sufficient level of abstraction is obtained. For pedestrian flows formed in the study site, the peculiarities of their formation, direction, and termination have been established. All this is formalized in the form of a parametric model and graphs. The obtained results allowed us to form a set of parameters and rules for their interaction to create a simulation model. In studies related to simulation modeling of transportation systems, the authors obtain similar in nature and structure results, which are the basis for creating models of behavior of each structural element of the problem domain [5, 6, 8, 13].

The created simulation model reflects all the main aspects of the problem domain and allows tracking of the behavior of groups of objects with the same behavior. As researchers point out in their works, in a real system, minor deviations are possible for individual instances in a group of objects with unique behavior [3, 7, 12]. This is also possible in the system under study when adjusting parameters for excluding events (e.g., pedestrian movement towards a flow moving in the opposite direction, pedestrian stopping in the center of a moving flow). The occurrence of such an event in the simulated system allows evaluating the behavior of all objects and implementing processes while preserving the established rules.

5 Conclusion

Modeling pedestrian flows occurring at subway stations is an important task. This is necessary not only for the arrangement of space, convenience, or safety of passenger movement in the lobby, on the escalator, or the platform but also allows to establish the carrying capacity of the subway line. In other words, whether trains can carry groups of passengers at stations at a certain interval. For stations that are part of an interchange hub, an important indicator is also the capacity of the interchange track: how many escalators should operate simultaneously so that large crowds of passengers do not form in front of it, whether pedestrian flows moving to the train, crossing or exit will be crossed.

When organizing the space in the station lobby, it is important to organize the movement of pedestrian flows so that the flows of passengers going to the turnstile to pass to the escalator do not intersect with a possible queue to purchase tickets. When organizing the space on the platform itself, it is important to establish places where passenger movement is minimal. These locations may include information desks, service facilities, or benches. All this creates a comfortable and safe environment. A simulation model is the primary way planned changes can be evaluated. The developed model and process implementation scenarios can demonstrate at a given time interval changes in the behavior of objects with some probability.

References

1. D.E. Ushakov, D.V. Karelin, *Evaluation of the Possibility of Forecasting the Passenger Flow of the Novosibirsk Metro on the Basis of Density of the Housing Stock, Socio-Economic Problems of Development and Functioning of Transportation Systems of Cities and Zones of Their Influence*, in D.V. Kapsky (ed.), Proceedings of the Conf., 126-136, Minsk, BNTU (2018)
2. D.T. Ospanov, D.E. Namiot, O.N. Pokusaev, Int. J. Open Inf. Tech. **11(6)**, 118-128 (2023)
3. M. Logachev, A. Tkachev, I. Nikishina, E3S WoC **363**, 02036 (2022). https://doi.org/10.1051/e3sconf/202236302036
4. A. Krasnikov, I. Nikishina, Yu. Laamarti, I. Voronin, I. Okhotnikov, I. Litvin, E3S WoC **363**, 02037 (2022). https://doi.org/10.1051/e3sconf/202236302037
5. Yu. Altunina, Yu. Laamarti, Kh. Kuchmezov, I. Zaichikova, I. Patsakula, E. Khachikyan, E3S WoC **363**, 02033 (2022). https://doi.org/10.1051/e3sconf/202236302033

6. M. Logachev, E. Tolkacheva, S. Shibaev, V. Chernova, A. Butyrin, E3S WoC **403**, 07011 (2023). https://doi.org/10.1051/e3sconf/202340307011
7. I. Nikishina, T. Karyagina, P. Mironov, V. Churin, E3S WoC **403**, 07017 (2023). https://doi.org/10.1051/e3sconf/202340307017
8. V.V. Fomin, N.E. Dubrovskikh, Modeling of Passenger Flow at Izmailovo Station of the Moscow Central Ring, Digital Evolution: Fundamentals of Information Society Development, in G.S. Zhukova (ed.), Collection of Scientific Articles, 169-175 (Rusains, Moscow, 2023)
9. L. Kazanskaya, E. Proskuryakova, Urban. Archit. Const. **12.1**, 5 (2021)
10. M. Logachev, V. Bugrimov, A. Kondratyev, Transp. Res. Proc. **63**, 2335-2340 (2022). https://doi.org/10.1016/j.trpro.2022.06.267
11. A. Krasnikov, I. Nikishina, N. Rebus, K. Grabovyy, E3S WoC **403**, 07002 (2023). https://doi.org/10.1051/e3sconf/202340307002
12. S. Sebastian, R. Fernandez, Transp. Res. Part C: Emer. Tech. **53**, 76-92 (2015)
13. B. Moaveni, S. Najafi, IEEE Trans. Cont. Sys. Tech. **26.5**, 1541-1551 (2017)
14. O. Korotun, A. Kolodochkin, Yu. Laamarti, A. Assylbayev, BIO Web Conf. **83**, 05006 (2024) https://doi.org/10.1051/bioconf/20248305006
15. M. Logachev, M. Zelenkov, BIO Web Conf. **107**, 04023 (2024) https://doi.org/10.1051/bioconf/202410704023