Simulation modeling as a tool for predicting pedestrian flows when planning a Moscow Metro surface station

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Abstract. The article substantiates the use of simulation modeling methods to organize efficient and safe passenger movement at the metro station. The list of key objects and their corresponding processes at ZIL station, a part of the Moscow Central Ring (surface line of the Moscow Metro), is determined using structural analysis methods. Based on the results obtained, the input parameters of the simulation model and the rules for realizing the processes corresponding to them were determined. Using specialized software tools, a 3D computer model has been developed that complies with the established rules and demonstrates all aspects of the subject area. Fragments of the model realizing certain scenarios of passenger movement through the station facilities are presented. The obtained model can be used to develop the concept of sustainable development of urban areas and transportation.

Keywords. 3D-model; structural analysis; transport; passenger flow.

1 Introduction

Simulation modeling is a rather effective way of forecasting possible changes from introducing new technical means into the subject area, modernization of infrastructure objects or processes. Such methods create a digital twin with all processes displaying object characteristics (e.g., structural and functional parameters, relationships) that are essential for the study purposes [1].

The creation of digital twins is justified for complex dynamical systems. This is because such systems are defined by objects and processes with a set of states (a set of qualitative and quantitative characteristics, interaction laws) that are valid at some point in time [2]. All this describes the evolution of the initial state over time. Dynamic systems, for example, include physical, biological, chemical objects, computational, transportation or information conversion processes [3].

The urban transportation system is a complex system that consists of a multifunctional structure that ensures the smooth movement of people and goods along specific routes. The quality and efficiency of urban transportation system play a crucial role in citizens’ economic

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life and welfare [4]. Any changes to such a system require a large amount of resources and the impossibility of conducting a full-scale experiment to assess the effects of such changes.

The main mode of transportation in Moscow is the subway, which is the basis of the city’s transportation system. The route network of urban ground transportation, location of infrastructure facilities are built in relation to the location of metro stations. Each station can be considered as a separate system consisting of flows of passengers and vehicles, infrastructure facilities that affect the organization of movement of these flows [5]. Traffic organization, planning of the territory adjacent to the station and arrangement of appropriate facilities affect the accessibility of transport, travel time, comfort and safety of passengers. It is necessary to create a digital twin that will allow different experiments to evaluate the effectiveness of concepts for the development of a transportation infrastructure facility to create an environment that meets the above requirements. This substantiates the relevance of the study.

The study aims to create a simulation model reflecting all key aspects of the problem domain to evaluate the effectiveness of its transformation concepts for sustainable development. Theoretical significance of the study lies in determining the role of simulation modeling in the city transport system when planning its sustainable development and obtaining a formal description of the system processes. The practical significance of the study lies in using the results for the development of urban planning plan of territories, concepts of transportation systems development and assessment of potential consequences from their implementation.

2 Materials and methods

The object of the study is traffic and pedestrian flows at the Moscow Central Ring station “ZIL”, located in Danilovsky district of the Southern Administrative District of Moscow. The station consists of an above-ground island platform and an elevated concourse. It was necessary to establish all elements and their corresponding characteristics to create a simulation model of the research object.

The step-by-step use of the structural analysis method allowed to identify the key elements of the research object. By decomposing the system with a specific level of abstraction at each level, an accurate description of the subject area was obtained. This approach in creating a simulation model is found in many research works of domestic and foreign scientists [6-9].

It was necessary to establish the rules of interaction of the established structural elements to create a digital twin simulating the processes of a real object. For this purpose, statistical analysis and parametric modeling methods were used [7, 10, 11]. Formal models demonstrating the behavior of the system elements were created using the graphical method to analyze the obtained results and determine the possibility of their further use [6, 8, 10].

Using specialized software tools, the identified elements, their qualitative and quantitative characteristics, and their rules were processed by simulation. As a result, a 3D model of the object was obtained, reflecting all aspects of the subject area with a given accuracy of the probability of its behavior over time [7, 11, 12].

3 Results

The Moscow Central Ring is the 14th line of the Moscow Metro, located entirely on the surface. Most stations are interchanges to other Moscow Metro lines and Moscow Central Diameters (rail transport lines connecting Moscow with nearby districts of Moscow Region) and interregional rail transport routes. The remaining non-transfer stations are the only access
points to the subway. All this determines high passenger traffic in all directions of travel. Figure 1 shows the statistics of passenger passes at ZIL station for 2021-2023.

![Figure 1. Passenger traffic at ZIL station of the Moscow Central Ring (compiled from the Moscow Government’s open data portal: https://data.mos.ru).](image)

ZIL station is located on the territory of the former industrial area, the area of reconstruction of which is 392 hectares. The railroad divides the territory into two areas, north and south. Each is designed to organize residential, leisure, business, educational and recreational areas. Upon completion of the project it is planned to create 66 thousand jobs and provide housing for 77 thousand residents [Complex of urban planning policy and construction of the city of Moscow: https://stroi.mos.ru/construction/2213]. The facilities are being delivered in phases and full construction is scheduled for completion in 2028. All this determines the gradual growth of passenger traffic at the station.

Five-car “Lastochka” trains are used for passenger transportation. Boarding and disembarkation of passengers is carried out through two doors in each car. Train traffic is organized according to weekday peak loads in the morning and evening. Figure 2-3 shows the number of trains passing through the station during weekday and weekend operation.

![Figure 2. Number of rolling stock at ZIL station of the Moscow Central Ring on a weekday.](image)
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The following rule is used to set train rules:

$$T = \frac{S}{n},$$

where $T$ is the interval of uniform train movement;

$S$ is the length of the entire ring in units of time;

$n$ is the number of trains.

The distance between trains in this case is determined by the formula (when $j > i$):

$$d(x_i, x_j) = x_j - x_i - (j - i)T$$

In this case, the model is a metric space whose distance value is independent of the choice of the initial point on the ring due to the difference in coordinates of the points on the ring [13]. The vehicle position potential $f(x_i)$ by the following rule:

$$f(x_i) = x_i - iT.$$ 

Accordingly, the greater the potential of a lineup position, the more difficult it is for laggards to catch up. The rule determines the difference between the potentials of the leading and lagging trains:

$$\Delta_{\text{max}} = \max f(x_i) - \min f(x_i).$$

In case of changes in the train operation mode (change in the number of trains from $n$ to $m$), $\Delta_{\text{max}}$ is determined by the formula:

$$\Delta_{\text{max}} = \frac{S(n - m - (n,m))}{n(n - m)}.$$ 

In this case, $\Delta_{\text{max}} < \frac{S}{n}$. 

Fig. 3. Number of rolling stock at ZIL station of the Moscow Central Ring on a day off.
Analysis of pedestrian density on the platform showed that the highest density of passengers is observed near the escalators. It is the shortest distance a passenger can travel after descending the escalator to a train in either direction of travel. The same high passenger density is seen in the car that will stop closer to the platform exit. It should be considered that each train’s capacity is 1.5 thousand passengers [Moscow Metro: https://mosmetro.ru/passengers/development/mcc/about].

When exiting the train, the microflows form into a common flow at the escalator to ascend to the concourse. A single escalator is also used to descend to the platform from the concourse. All of this increases crowding at peak times to exit the platform, and crossing flows occur. In addition to the escalator, the station has stairs and an elevator, which many passengers do not use.

A structural analysis of the concourse zoning showed the following areas for ticketing (two ticket offices and vending machines), baggage screening, fare payment, and waiting for the train. Exit the concourse into a two-way ground crosswalk. Thus, before entering the concourse, pedestrian flows are combined into one in front of the inspection area, then they can split: one microflow will move to the fare payment area, the other – to buy a ticket. Figures 4-5 shows the patterns of passenger behavior.
Such models and established rules for trains are the basis for the simulation model. Figure 6-10 presents a 3D model visualizing the results of the structural analysis of the problem domain and parametric modeling.

**Fig. 6.** 3D model simulating passenger boarding and disembarkation.

**Fig. 7.** 3D model simulating inspection and fare collection area.

**Fig. 8.** 3D model simulating pedestrian movement along the transition to the concourse.

**Fig. 9.** 3D model simulating the scenario of passenger traffic increase at peak time.
The resulting 3D model allows the characteristics of objects to be modified to predict changes over time. Such characteristics include passenger boarding and disembarkation times, train interval, modes and speed of escalators, number of passengers, organization of space in the concourse or on the platform (e.g., installation of vending machines, benches, interior items), etc. The visualization of objects is simplified to reduce the load on the computational resources of the computer producing the simulation processes (e.g., textures and detailed animation of pedestrians are not used). This does not affect the accuracy of the predictions of the implementation of behavioral scenarios for each element of the subject area.

4 Discussion

Simulation modeling implements the iterative nature of system model development and greatly enhances the capabilities and efficiency of professionals making decisions on infrastructure modernization or process control [1]. In studies related to simulation modeling, a step-by-step detailing of the objects of the problem domain is carried out with the extraction of their structure [3, 4, 7, 9]. The study analyzes such a domain by identifying all the key entities, their corresponding characteristics and interaction rules.

The obtained results are processed and formalized to be used in a simulation model. For this purpose, behavior models of key entities affecting the problem domain have been developed. As researchers point out in their works, a behavior model is actually one way of describing objects’ algorithms in different situations [8, 11, 12]. The paper establishes the basic algorithms passengers perform in a subway station. Based on the obtained results, a 3D model is developed, which visualizes the functioning of the simulation model on a certain time interval with the specified parameters of objects [14-16].

5 Conclusion

Simulation modeling, one of the types of computer modeling, allows creating a digital twin with a set of all characteristics and factors of the real system for different computational experiments. At the same time, the developed model does not provide a solution to the optimization problem, but is an additional tool for the analyst to find a solution to the defined problem. In fact, such an expert performs the setting of a directed computational experiment using the developed model, evaluating the results according to the created criteria to manage the decision-making process. Multiple use of the simulation model at different specified input parameters allows to obtain a comprehensive assessment of the obtained values during its operation.
This approach is particularly important in the development of any transportation system in a community. The larger the settlement, the more complex such a system is organized due to multiple objects and related processes. All this requires analyzing a large number of factors with different origins. This is because transportation systems processes depend on the day of the week, time of day, site location, pedestrian density, weather conditions, space organization, etc. Using modern tools to assess or predict the impacts of transportation modernization decisions allows for a safe, accessible, environmentally friendly, and sustainable environment for the public.

References