Mechanics Transport Communications
Academic journal http://www.mtc-aj.com
ISSN 1312-3823 (print)
ISSN 2367-6620 (online)
volume 23, issue 3, 2025
article № 2702

MODELING OF TECHNOLOGICAL OPERATIONS OF RAILWAY STATIONS

Mihail Rangelov
mrangelov@vtu.bg

Todor Kableshkov University of Transport,
Sofia, Geo Milev Str. 158,
BULGARIA

Abstract: *The process of modeling technological operations performed at railway stations is applied in the organization of work, increasing efficiency and improving the management of railway transport. Modeling is considered as a tool for analyzing and predicting the behavior of complex logistics systems under different operating conditions. The main technological processes of stations are presented - receiving and sending trains, shunting work, downtime, distribution on tracks and servicing loading and unloading operations. Emphasis is placed on the use of mathematical models, simulation techniques and information systems, through which virtual copies of real processes are created. It is necessary to consider different approaches to optimizing train schedules, infrastructure capacity and the use of available resources. An important element is the study of the possibilities for applying digital technologies and artificial intelligence to automate technological processes at stations and increase the accuracy of decision-making. The advantages of applying modeling in planning the reconstruction of existing stations or the construction of new ones, as well as in developing adaptive real-time control systems, are noted. The article emphasizes the role of modeling as a tool for making informed decisions in the design, operation and modernization of railway stations in accordance with modern requirements for transport sustainability and digitalization.*

Key words*: modeling of technological operations, mathematical modeling, simulation modeling,*

INTRODUCTION

Railway stations are key elements of the railway infrastructure, performing critical functions in the logistics chain of the transport system. They serve as nodes for transfer, shunting, stopping and loading and unloading activities, which requires precise coordination and effective management of resources. Various types of operations are carried out in the stations - technical, commercial and operational, which must be synchronized in order to avoid delays, capacity overload and inefficient use of the infrastructure. In the conditions of increasing transport intensity, urbanization and the need for sustainable development, railway transport plays an increasingly important role as an ecological and energy-efficient alternative.

This places new demands on the stations - they must meet high standards of efficiency, safety and adaptability to the changing environment. In this context, modeling of technological operations in stations is established as an important tool for analysis and optimization. It allows simulating real scenarios, identifying "bottlenecks" in logistics processes, as well as studying the effects of various management decisions and investment initiatives. The purpose of this article is to present the main technological processes in railway stations, the methods for their modeling, as well as the potential of modern technologies for improving the efficiency, sustainability and competitiveness of railway transport.

1. OVERVIEW OF TECHNOLOGICAL OPERATIONS AT RAILWAY STATIONS

The technological process at a railway station begins with preparation for the reception of a train. Dispatchers check the availability and condition of the tracks, routes and signaling. At the same time, conditions are prepared for the safe entry of the train. When arriving, the train enters a given route and stops on a certain track. Its technical condition is checked, and the arrival is documented. The driver, station technician and station duty officer are involved here.

After arrival, the train may remain idle. For passenger trains, this includes passenger service and sanitary activities, and for freight trains - waiting for maneuvers or loading and unloading operations. Service personnel and shunting teams are involved. Shunting activities include moving and arranging wagons, as well as forming new trains. It is performed by a shunting locomotive with the help of a driver and switchmen, under the supervision of the station dispatcher. If necessary, loading and unloading operations are carried out using cranes or other equipment. The process is managed by operators and warehousemen, and the control is carried out by representatives of the railway operator.

After the completion of maneuvers and loading, a train is formed for departure. Checks are carried out and a locomotive is assigned. Upon receipt of permission from the dispatcher, the train departs for the next station. Finally, the track is cleared and prepared for new traffic. This ensures continuous and efficient operation of the station.

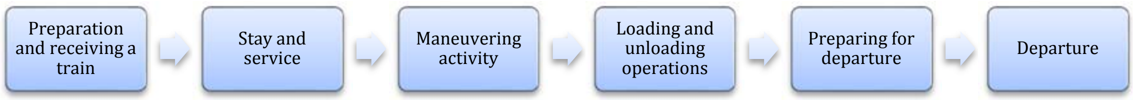

Fig. 1. Sequence of technological operations at a railway station

Modeling the technological process in railway stations is necessary to increase the efficiency, safety and sustainability of rail transport. Station operations are complex, dynamic and often subject to unforeseen situations such as delays, overloading or technical failures. Through modeling, virtual replicas of real processes are created, which allow analysis, optimization and prediction of different scenarios without risk to real operation.

2. MODELING APPROACHES

Modeling of technological processes can be implemented through different approaches.

Mathematical models allow formalization of dependencies and derivation of optimal solutions. Simulation techniques – especially discrete-event simulation – allow creation of virtual models of stations and analysis of their behavior under different conditions. Also, information systems and so-called "digital twins" are established as tools for monitoring, planning and management.

Table 1. Comparison of modeling methods

Method	Application	Advantages	Disadvantages
Mathematical modeling	Train Schedule optimization	Accurate results	Simplification is needed
Simulation modeling	Evaluation of scenarios	Flexibility, realistic	Requires lots of data
AI	Prognosing, optimization	Adaptivity	Needs a lot of data to train

2.1 Mathematical modeling

Mathematical modeling is the process of creating abstract, mathematical representations of real systems for the purpose of analyzing, optimizing, and predicting their behavior. In the context of technological operations in stations, mathematical modeling is used to describe and optimize processes such as train allocation on tracks, shunting planning, and cargo handling. By building models based on algorithms and equations, different scenarios can be simulated, bottlenecks in operations can be identified, and more informed decisions can be made to increase efficiency and safety at railway junctions.

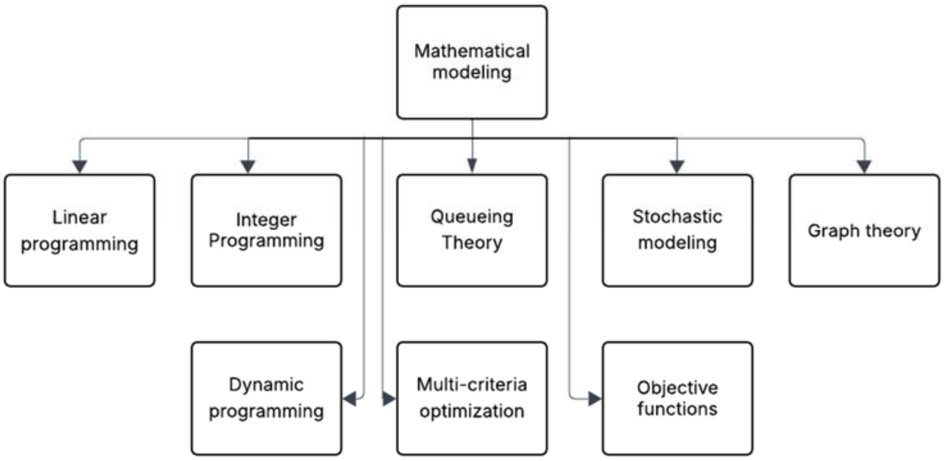

Fig. 2. Types of mathematical modeling

Linear (LP) and integer programming (Integer Programming)

Linear programming is a mathematical method for optimizing an objective function under linear constraints. In the context of railway stations, it can be used to minimize train dwell times, optimally allocate resources such as tracks and locomotives, and synchronize schedules. It can be used to optimize the allocation of trains to tracks so as to minimize the total dwell time at the station. Integer programming is an extension of linear programming in which some or all variables must take only integer values. A specific example is the problem of routing and scheduling trains in a station environment. [1].

Queueing Theory

The theory of the SMO models the waiting processes characteristic of the stay and reception of trains. With its help, average waiting times, the number of trains waiting and the efficiency of the station's service facilities can be estimated. In the given example, the theory of the QT is used to predict and optimize the freight cars in the Varna ferry station [2].

Stochastic modeling

Stochastic modeling considers processes of a random nature – for example, train delays, accidents or irregular flows. It uses probabilistic methods and simulations to analyze the behavior of the system under various conditions of uncertainty. A study examined considers the capacity of the railway network using stochastic variables for travel time, blocking and permissible intervals between trains (buffer times) [3].

Graph theory

Graph theory is widely used in the modeling of railway infrastructure as a network of nodes (objects) and edges (connections). It allows for the discovery of optimal routes for movement, conflict avoidance, and analysis of system connectivity. Graph theory has been used in the context of complex, multi-layered networks to model railway infrastructure and technological processes. [4].

Dynamic programming

Dynamic programming is an approach to solving complex problems by dividing them into smaller subproblems. It is applied to staged planning of maneuvers, determining sequences of actions, and optimizing solutions over time. In the given example, the authors formulate a nonlinear integer model for synchronizing arriving and departing trains at a transfer station [5].

Multi-criteria optimization

This approach simultaneously considers several criteria – for example, minimum time, minimum costs and maximum reliability. It is suitable for making strategic decisions for the development and modernization of station infrastructure. It has been applied to the Bulgarian railway network for the preparation of transport plans for intercity trains, comparing different options according to criteria such as operating costs, travel time, number of stops, reliability and passenger satisfaction. [6].

Objective functions – minimax/maximin models

Minimax and maximin models are used in the presence of risk and uncertainty, when the best of the worst possible scenarios is sought. They ensure the system's resilience under adverse conditions and help with reliable planning. In the example given, the authors formulate a minimax optimization model aimed at minimizing the largest delay of groups of passengers in a high-speed rail network [7].

2.2 Simulation modeling

Simulation modeling allows the creation of virtual copies of stations that can be used to test different scenarios. Commonly used approaches are discrete-event simulation, agent-based modeling, and hybrid methods. They are applied to evaluate operational strategies, load analysis, and behavior in emergency situations.

DES – Discrete-Event Simulation

Essence: Models the system through a sequence of clearly defined events (e.g. arrival, shunting, loading) that occur at a specific point in time. It finds application in schedule optimization, capacity and conflict management, and downtime minimization. The article develops a model applying DES to simulate train and passenger traffic at Baltiyskaya Station in St. Petersburg, Russia [8].

ABM – Agent-Based Modeling

Essence: Describes the system as an interaction of individual agents (trains, locomotives, operators), each with its own behavior and goals. In the context of technological operations in stations, ABM allows detailed tracking of the interaction between different actors such as locomotives, wagons, shunters and dispatchers. A typical example considers interactions between agents (trains, infrastructure elements, operators) and their reactions to deviations and violations [9].

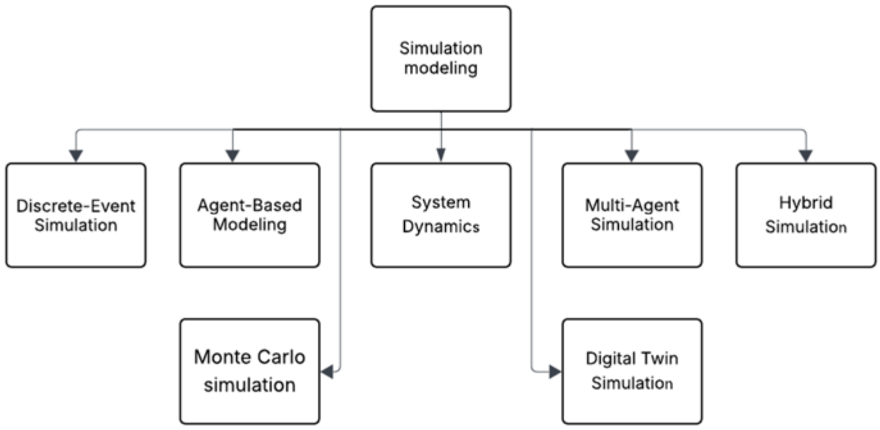

Fig. 3. Types of simulation modeling

System Dynamics

Essence: Focuses on flows and accumulations in the system – capacity, load, resources – using differential equations and cause-and-effect relationships. In the field of station operations, system dynamics is used to study the long-term behavior of systems such as train handling, track capacity, and facility utilization. For example, the system dynamics model, a two-level approach that combines macroscopic aspects such as infrastructure capacity and transport mode, with microscopic variables such as speed and passenger route choice, described in [10]

MAS – Multi-Agent Simulation

Essence: Extends ABM, allowing coordination between multiple agents with a common goal (e.g., train dispatching and signaling). Can be used to study interactions between trains, dispatchers, and automated systems in real time. Example – development of a module for distributing passengers across platforms in a large high-speed railway station, discussed in [11].

Hybrid Simulation

Essence: Combines several simulation approaches – for example, DES for events and ABM for agent behavior – into a single model. It finds application in building a comprehensive simulation environment, covering both process logic and individual decisions.

Monte Carlo simulation

The Monte Carlo model is a stochastic modeling method that uses repeated random simulations to evaluate the behavior of a system under various conditions of uncertainty. In modeling technological operations in stations, the Monte Carlo method is applied to analyze variables such as train arrival times, loading and unloading durations, and the occurrence of delays. A specific example of the use of this simulation to determine the duration of a railway station construction project in Jakarta, Indonesia is shown in [12].

Digital Twin Simulation

Essence: Connects a virtual model with real-time data from systems, sensors and graphs. It is used for real-time monitoring and control. Virtual digital twins are digital copies of real objects, systems or processes that reflect their real-time behavior through data from sensors, algorithms and simulations. In the considered example, a digital twin of a railway station is proposed, which simulates various emergency scenarios (fire, flood, social and health incidents) on the Beijing - Zhangjiakou high-speed line [13].

2.3. Artificial Intelligence and Machine Learning

Artificial intelligence methods, such as neural networks, genetic algorithms and reinforcement learning, are used to predict traffic, recognize recurring patterns and optimize complex systems. Machine learning allows information systems to adapt to the dynamic environment of stations and improve the accuracy of predictions over time. A typical example is the AI-based system introduced in China for modeling and restoring the technological process (schedules) in the railway network in the event of disruptions (delays, accidents). [14].

CONCLUSION

Modelling technological operations of railway stations is a powerful tool for improving the efficiency, sustainability and digitalization of railway transport. With the help of mathematical, simulation and information approaches, railway operators can optimize their processes, reduce delays and increase the throughput of stations. The development of digital technologies and their integration into the transport infrastructure creates new opportunities for automation, forecasting and intelligent management.

The presence of different and diverse methods for modeling railway station technology, shown in this paper, shows the need for careful selection of the type of modeling. This selection should consider both the type of task, the advantages and disadvantages of different models. The correct choice of model, in addition to achieving the required result, also translates into savings in labor, time and money, as well as overall higher efficiency.

REFERENCES:

[1] Bai, L., Bourdeaud'huy, T., Rabenasolo, B., & Castelain, E. (2014). *A mixed-integer linear program for routing and scheduling trains through a railway station*. В International Conference on Operations Research and Enterprise Systems (ICORES-2014) (стр. 445–452). DOI:10.5220/0004863104450452

[2] Todorova, M., & Rangelov, M. (2025). Modeling the technology of the Varna ferry complex operation using the queueing theory. In Environment. Technology. Resources. Proceedings of the 16th International Scientific and Practical Conference (Vol. 4, pp. 419–424). Rezekne, Latvia. https://doi.org/10.17770/etr2025vol4.8395

[3] Hansen, I. A. (2004). Optimisation of railway capacity use by stochastic modelling. In Traffic and Transportation Studies Conference (ICTTS) (pp. 1–10). Dalian, China: Science Press.

[4] Gao, P., Zheng, W., Liu, J., & Wu, D. (2025). Research on modeling and analysis methods of railway station yard diagrams based on multi-layer complex networks. Applied Sciences, 15(5), 2324. https://doi.org/10.3390/app15052324

[5] Tian, X., & Niu, H. (2017). A dynamic programming approach to synchronize train timetables. Advances in Mechanical Engineering, 9(6), 1–11. https://doi.org/10.1177/1687814017712364

[6] Tomov, K., Dimitrov, P., & Ivanova, M. (2020). An integrated multi-criteria and multi-objective optimization approach for establishing the transport plan of intercity trains. Sustainability, 12(2), 687. https://doi.org/10.3390/su12020687
[7] Bersani, C., del Cacho Estil-les, M. A., & Sacile, R. (2021). Min-Max Approach for High-Speed Train Scheduling and Rescheduling Models. IEEE Access. https://doi.org/10.1109/ACCESS.2021.3064427
[8] Kuzmin, D., Baginova, V., & Ageikin, A. (2022). *Discrete event simulation model of the railway station*. Transportation Research Procedia, 63, 1291–1298. https://doi.org/10.1016/j.trpro.2022.06.149
[9] Kongsap, S., & Kaewunruen, S. (2024). Agent-Based Modelling of High-Speed Railway Interdependent Critical Infrastructure. Frontiers in Built Environment. https://doi.org/10.3389/fbuil.2024.1249584
[10] Zhang, Z., Jia, L. & Li, S. (2020). System dynamic model and algorithm of railway station passengers distribution. In Proceedings of the 4th International Conference on Electrical and Information Technologies for Rail Transportation (EITRT 2019) (pp. 513–523). Singapore: Springer. https://doi.org/10.1007/978-981-15-2914-6_48
[11] Zhang, H., Li, B., & Wang, Y. et al. (2023). A multi-agent simulation based train platforming research for facilitating passenger transfer in a high-speed railway station. Simulation Modelling Practice and Theory, 130, 102856. https://doi.org/10.1016/j.simpat.2023.102856
[12] Iqbal, R., Santana, J., & Aryandono, T. (2024). Monte Carlo Simulation for Enhancing the Schedule Completion Forecast of Jakarta Central Railway Station Construction Project. Applied Sciences, 15, 7464. https://doi.org/10.3390/app15137464
[13] Zhang, J., Wang, M., & Sun, L. (2023). *Digital twin for multi-scenario emergency of railway passenger stations*. Frontiers in Physics, 11:1291785. https://doi.org/10.3389/fphy.2023.1291785
[14] Xie, Y., Zhao, Y., Li, Y., & Zhou, X. (2022). Artificial intelligence–empowered resilience-oriented railway timetable rescheduling: A framework and case study. *Transportation Research Part C: Emerging Technologies*, 140, 103717. https://doi.org/10.1016/j.trc.2022.103717

МОДЕЛИРАНЕ НА ТЕХНОЛОГИЧНИ ОПЕРАЦИИ НА ЖЕЛЕЗОПЪТНИ ГАРИ

Михаил Рангелов
mrangelov@vtu.bg

Висше транспортно училище „Тодор Каблешков",
ул. „Гео Милев" 158, София 1574,
БЪЛГАРИЯ

Резюме: *Процесът на моделиране на технологични операции, извършвани на железопътните гари, се прилага в организацията на труда, повишаване на ефективността и подобряване на управлението на железопътния транспорт. Моделирането се разглежда като инструмент за анализ и прогнозиране на поведението на сложни логистични системи при различни експлоатационни условия. Представени са основните технологични процеси на гарите - приемане и изпращане на влакове, маневрена работа, престой, разпределение по коловози и обслужване на товаро-разтоварни операции. Акцентът е поставен върху използването на математически модели, симулационни техники и информационни системи, чрез които се създават виртуални копия на реални процеси. Необходимо е да се разгледат различни подходи за оптимизиране на графиците на влаковете, капацитета на инфраструктурата и използването на наличните ресурси. Важен елемент е изучаването на възможностите за прилагане на цифрови технологии и изкуствен интелект за автоматизиране на технологичните процеси на гарите и повишаване на точността на вземане на решения. Отбелязват се предимствата от прилагането на моделиране при планирането на реконструкцията на съществуващи гари или изграждането на нови, както и при разработването на адаптивни системи за управление в реално време. Статията акцентира върху ролята на моделирането като инструмент за вземане на информирани решения при проектирането, експлоатацията и модернизацията на железопътните гари в съответствие със съвременните изисквания за устойчивост на транспорта и дигитализация.*

Ключови думи: *моделиране на технологични операции, математическо моделиране, симулационно моделиране,*