

DIGITAL TWINS OF RAILWAY JUNCTIONS BASED ON A SIMULATION MODEL

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Abstract

The development of information technologies and technical devices for registering raw data is the basis for providing simulation models of railway transport with real data. The article presents a solution for using the universal AnyLogic simulation tool to build a digital twin of a railway junction. The main problems of using simulation models for constructing digital twins of railway junctions are revealed: formalization of rail track topology, description of the operational rules, synchronization of model and real data. The three-layer architecture of the digital twin of the railway junction and its possibilities for solving the identified problems are presented.

Key words: *digital twin, railway junction, simulation modeling, AnyLogic, ITS, synchronization.*

1 INTRODUCTION

Digital twins are an element of the Industry 4.0 concept [1]. Their development is associated with the improvement of information technologies, blockchain technology [2], as well as the active spread of the Internet of things [3]. The dissemination of these technologies made it possible to obtain operational data on various parameters of the transportation process. This created the prerequisites for using the current raw data for decision-making.

Digital twins in railway transport are now beginning to be used to solve a variety of tasks related to the management of railway infrastructure, rolling stock, and transportation. The emergence and development of digital twins made it possible to use a variety of mathematical methods and models in the operational management of transportation. Such methods are divided into three large groups:

analytical, simulation and combined [4], [5]. They have traditionally been used to solve problems of planning, strategic management, as well as the development of transport infrastructure.

Simulation tools for transport systems are potentially capable for creating digital twins of dynamic production and transport facilities [6]. The use of simulation tools to build digital twins requires solving the problem of synchronizing the data of the simulation model with real data.

Most of the known rail transport simulation tools are asynchronous. Asynchronous tools operate on a predetermined schedule and are used primarily to estimate the capacity of the rail network [5].

Typical examples of an asynchronous approach to modeling railway transport are the RTC system (Rail Traffic Controller system) [7], [4], RailSys [8], [9], OpenTrack [10], SYSTRA's RAILSIM X [11], and ISTRASIM [12].

Asynchronous simulation models of operation and control in railway transport are used mainly to develop and control train schedules, as well as optimize the operation of marshalling yards. The work of such main lines yards is to perform simple shunting operations. The set of these operations is limited and known in advance. Optimizing the order and composition of these operations is not an NP-hard task.

Synchronous simulation tools, in contrast to asynchronous ones, require additional hardware or software to synchronize real and model events [4]. Synchronous modeling is currently used to a limited extent to control the train schedule [13], as well as to optimize the routes of freight trains in the Swiss control system for rail freight Single Wagonload (SWL) [14].

Railway junctions, including industrial sidings, operate in an environment of high uncertainty. This is due to the need to serve a multitude of loading / unloading areas, consumers of transport services, cargo owners with a stochastic demand for transportation. Complex shunting operations are carried out at railway junctions to deliver railcars to loading / unloading areas. These operations are performed by the backup shunting method using draw-out tracks. The task of optimizing the parameters and the sequence of shunting operations is NP-difficult due to the large number of options for their implementation. This feature of railway junctions increases the need to create their digital twins to support decisions. On the other hand, there is a need to solve several fundamental problems associated with the complexity of the structure and functions of railway junctions. We propose to distinguish three levels of problems creating of railway junctions' digital twins (RJDT).

The first level problems are related to the description of the rail track topology of railway junctions. Rail track topology should provide for the ability to determine the optimal route for a shunting train. The problem of the second level is to create a mechanism for operational planning of the sequence of operations of the technological process (operational rules) of the railway junction.

Finally, the problem of the third level is the synchronization of the model situation with the real data of the railway information system or an intelligent transport system (ITS).

This paper contains a description of specific solutions to problems of the first and second levels using the versatile AnyLogic simulation tool. In addition, the concept of integrating the RJDT into an ITS is presented.

The rest of the paper is organized as follows. Section 2 provides a brief overview of existing rail transport simulation tools and systems. Section 3 presents the structure and functions of the RJDT. Finally, the conclusion contains the findings, results, and a description of promising directions for the development of the RJDT.

2 LITERATURE REVIEW

We did not aim to systematically review research on digital twins and rail simulation tools. However, research analysis reveals a limited number of publications about digital twins of railway networks, rail yards and junctions. Most of the research in the field of using digital twins in railway transport concerns the application of this technology to monitor the technical condition of railway infrastructure and rolling stock.

Nevertheless, research is underway in the field of building digital twins of railway infrastructure in the form of a two-layer architecture (micro-level and macro-level) [15], as well as a multilayer architecture [16]. Also known is the digital twin of the freight yard [17], and the digital twin of the operational (dispatch) control of the rail yard, which supports decision-making [18].

Simulation models in railway transport are now widely used, mainly for solving problems of strategic and current planning, identifying “bottlenecks” and substantiating decisions on the development or reconstruction of transport infrastructure.

Simulation models are built to solve problems at the macro, meso and micro levels. Dedicated and versatile simulation tools are used to build these models.

OpenTrack [19], [10], FRISO [20], YardSim [21], DEVS [22] are mainly focused on the modeling of rail yards at the micro level. These systems ensure the resolution of conflict situations on the simultaneous occupation of tracks and turnouts when the train moves in one direction, that is, without changing the direction of movement. Flow diagrams (discrete-event approach) or different mathematical methods, neural networks [23] for example, is used for modeling the logic of performing railcar classification at such rail yards.

Reviews of micromodeling systems of rail yards with an analysis of the problems of their use are presented in [24] and [25].

SIMCON's Villon modeling tool [26], in addition to marshalling and passenger yards, allows simulating industrial sidings, container terminals and other transport infrastructure facilities. Villon is based on an object-based approach [27]. The program allows integration with optimization tools such as OptiYard [28], [29].

In most cases, railway junctions are modeled at the macro level. For these purposes, both universal modeling tools are used, for example AnyLogic [30], [31] and SIMUL'8 [32], and specialized tools, for example IMETRA [33]. In all these cases, each rail yard or yard area is modeled by a separate block of a discrete-event simulation model.

We managed to find the only study to date [34] in which a railway junction is viewed simultaneously at the macroscopic and microscopic levels. The authors consider the tactical and operational levels of planning the work of the railway junction.

In addition to specialized tools for modeling railway transport, universal simulation tools are actively used, for example AnyLogic [30], Arena [35], Plant Simulation [36], FlexSim [37]. Most of them, besides AnyLogic, support only one — the discrete-event paradigm of simulation.

However, recently, the popularity of the agent-based approach to modeling, including rail transport at the micro level, has been growing. The analysis of programs for constructing agent-based simulation models is presented in [38].

Universal environments, tools, and programming languages for creating multiagent simulation models [39] can potentially be used to create digital twins of rail yards and junctions. However, this requires additional programming to create specialized transport objects and libraries of such objects. Nevertheless, some tools, for example AnyLogic, contain ready-made libraries for agent-based modeling of railway transport. In addition, AnyLogic supports all known approaches to simulation modeling, including, in addition to agent-based, discrete-event and system-dynamic.

We chose AnyLogic as a tool for building digital twins of railway junctions and networks due to the possibility of implementing various simulation paradigms within a single model. In addition, AnyLogic is a versatile and affordable software platform with extensive support. This fact contributes to a wider distribution of models created with AnyLogic in comparison with specialized tools.

3 STRUCTURE AND FUNCTIONS OF THE RAILWAY JUNCTION DIGITAL TWIN

We propose a three-layer architecture of the RJDT (Fig. 1), which is an extension of the multilayer model [40]. The main difference of our model is the transfer of some routine operations to the base layer of the rail track topology description. Such operations include solutions for planning train routes on a railway network of complex topology, as well as blocking railway tracks and turnouts, as well as resolving conflicts when using these infrastructures elements.

The first layer of the proposed railway junction digital twin architecture includes a method for constructing a rail track topology. The presented method makes it possible to implement low-level optimization of the decisions made, for example, the choice of train routes, the execution of shunting operations.

The second layer simulates the management of the transportation process, rail cars flows and train schedules of the railway junction. Management consists in the selection of the composition and sequence of the actions from operational rules or work technique.

Finally, the third layer of the digital twin of the railway station provides synchronization of the model data with the real data of the ITS, as well as training the simulation model.

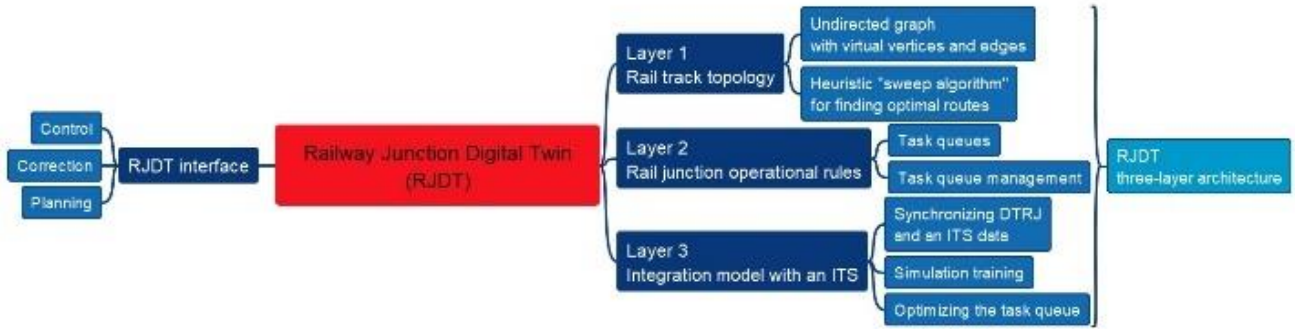


Fig. 1 RJD architecture

3.1. Rail Track Topology

The problem of using universal simulation tools to describe complex systems with specific functions is that these specific features are not sufficiently considered. Despite the presence of a specialized railway library in AnyLogic, it still does not solve the problem of resolving conflicts when trains occupy the same tracks and turnouts. We identify at least three approaches to solving this problem.

The first approach is based on the representation of individual tracks and turnouts as resources that are sequentially occupied and released as the train moves. Such a scheme is used, for example, in [41] (Arena) and in [42] (AnyLogic). The disadvantage of this approach is the laboriousness of creating many flow diagrams for each train route and the limitations on optimizing these routes.

The new approach proposed by AnyLogic [43] is based on the use of the Markov Decision Process [44]. The turnout switches direction and gives preference to the train that reaches the turnout faster. However, this approach contradicts the safety requirements for rail transport. The train route, consisting of a sequence of tracks and turnouts, must be formed in advance, and blocked for the movement of other trains. In addition, the flowchart of the simulation model must contain blocks for comparing train speeds.

Both approaches considered do not allow optimizing low-level operations for choosing the optimal train routes with the possibility of changing the direction of train movement. For example, in Fig. 2 shows a diagram of a turnout switch presented in the traditional form of an undirected graph. The edges of the graph are characterized by initial i , final j vertices and length L . The movement of the train from vertex 1 to vertex 4 is carried out along the route $R1$ and requires two shunting operations. The first operation is performed along the route $R3$. Then there is a change in the direction of movement, and the train moves along the route $\{3, 2, 4\}$. However, the route from vertex 3 to vertex 4 is not part of the optimal route $R2$ if the rail track topology is described by a traditional undirected graph. In the table of optimal routes (Fig. 2), the value λ_i is equal to the number of the vertex that precedes the i -th one, and $L_{\lambda_i i}$ is the length of the edge between the vertices λ_i and i .

Thus, the search for the optimal route from vertex 1 to vertex 4 using the traditional approach will lead to an erroneous display of the train route in the simulation model. Such a description of the rail track topology does not allow planning and optimizing complex train routes through the

rail yard and shunting operations with a change in the direction of train movement.

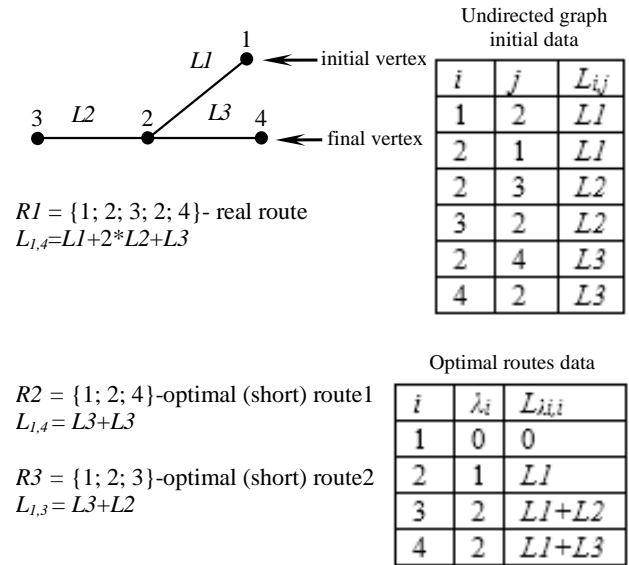


Fig. 2 Rail track topology as an undirected graph

We propose a third approach based on the automated formation of a virtual graph, in which two vertices are assigned to each vertex-turnout, for example, vertices 2 and 5 (Fig. 3). The virtual vertex is connected at the vertex-main track of the turnout switch by a virtual edge, for example (5,3). Correct optimal route $R1 = \{1; 5; 3; 2; 4\}$ is generated in the simulation model as a result of such a transformation.

The idea of a graph with two vertices for describing rail track topology was first proposed in [45]. Such a graph makes it possible to determine the optimal train routes along a railway station with a complex rail track topology. It becomes possible to change the direction of movement of the train on the turnouts to reach the specified end point of the route, regardless of the complexity of the rail track topology.

The optimal route for a train along the transport network can be calculated using various methods, for example [46]. We suggest using a fast heuristic “sweep algorithm” [47]. The idea of this algorithm is based on a sequential check for each i -th vertex of the graph of the following condition

$$L_{i=0,i} < L_{i=0,\lambda_i}, \quad (1)$$

where $L_{i=0,i}$, $L_{i=0,\lambda_i}$, respectively, the length of the route from the initial vertex $i = 0$ to the i -th and preceding vertices.

Vertex i is included in the optimal route only if condition (1) is met.

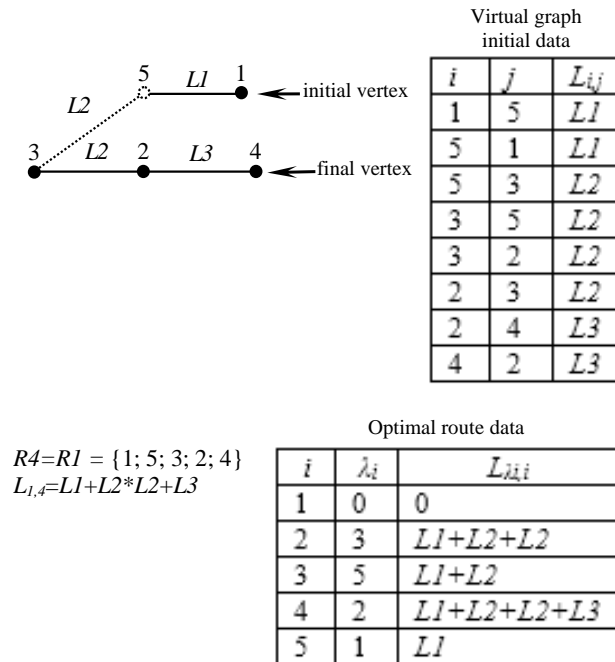


Fig. 3 Rail track topology as a virtual graph

This efficient algorithm allows finding all optimal routes from one or more initial vertices of the transport network to all other vertices.

This property of the algorithm is useful for optimizing train traffic priorities by comparing the indicators of their routes on the second layer of the digital twin. The model excludes from the calculation of routes at the next stage of operational planning all the edges of the graph included in the selected and planned route of the train movement. Thus, the simulation model considers blocking of tracks and eliminates conflicts during train movement.

3.2. Rail Junction Operational Rules

We propose to simulate the work of railway junctions and rail yards in the form of a set of tasks. A task is a set of data containing destination (vertex of the virtual rail track network), delivery time (desired time), quality (rail cars with a certain type of goods), quantity (number of rail cars). This set of data encapsulated in digital twin agents' dynamics type. Such agents are rail cars, groups of rail cars, locomotives, and trains. The task parameters are the same for all cars that make up block trains, but they are different for pickup freight trains.

The datasets defining tasks are passed in the form of messages between agents - managers at different levels. For a railway junction serving several industrial enterprises, cargo consumers, cargo producers or loading / unloading areas, the digital twin provides the following management

levels: production dispatcher or cargo owner, rail car fleet dispatcher, train dispatcher, and shunting dispatcher.

The main function of the production dispatcher is to formulate a task for the supply of rail cars with certain goods. The model transmits task data to railway dispatchers in the form of messages. The parameters of the production dispatcher tasks are determined by the dynamics of consumption of goods based on data, for example, inventory management systems or data from production information systems.

The rail car fleet dispatcher draws up an operational plan for the distribution of empty rail cars in the junction, that is, determines the parameters of the task for each empty rail car in the digital twin.

The functions of the train dispatcher are the formation of trains based on the distribution plan of rail cars and train scheduling. The train dispatcher plans the train routes in the model based on the enlarged topology of the railway junction. The vertices correspond to loading / unloading areas and entire rail yards, and the edges correspond to the tracks between stations. The train dispatcher, in terms of the digital twin, forms tasks for groups of cars, locomotives, and trains.

Finally, the shunting dispatcher forms tasks for the movement of trains within a separate rail yard of the railway junction, considering its rail track topology.

Determining the composition of the task queue and changing the order of their execution is the essence of management at all levels. The proposed rail junction operational technology provides three ways to form and change the task queue.

The first method provides for the automatic formation of a task queue based on operational rules. These rules include the schedule and plan for the formation of trains, flow diagram work of the rail yard, as well as the planned volumes of loading / unloading. This method is currently used in asynchronous simulation models of railway transport. The operational rules parameters are assumed to be optimal for the average traffic demand.

The second method allows manual adjustment of the composition and sequence of tasks at each management level, depending on the topical situation.

The digital twin interface allows managers to quickly change the contents of the task queue. Such an adjustment is necessary when the demand for transportation and the topical parameters of rail car traffic deviates from the average or standard values. Dispatchers can receive real data both using traditional communication equipment and from an ITS.

The third method is based on the use of various optimization algorithms to adjust the operational rules of the railway junction. For example, the methods developed by the authors for the distribution of empty cars [48], [49], control of shunting work at the rail yards of the railway junction [50].

The implementation of the third method requires tight integration of the digital twin of the railway junction into the existing ITS to obtain real data.

3.3. Integration Model with an ITS

The functional composition of ITS of railway junctions is presented in [51]. ITS, unlike information systems, provide support for management decisions. RJDTs are potentially capable of supporting optimal management decisions at all levels of rail hub management.

We propose integration model RJDT with an ITS. The proposed model consists of three functional blocks: a raw data synchronization block, a training block, and a decision support block. The first block provides synchronization of rail cars, locomotive, and train data between RJDT and ITS. This data includes data about the parameters of these dynamic objects in the system, including their locations on the railway tracks. The use of a simulation model in a digital twin makes it possible to predict the position of the rolling stock after performing the operations of the technological process (tasks in simulation model).

This property of RJDT makes it possible to reduce investment costs for the deployment of operational control systems for the movement of trains and locomotives, based, for example, on RFID technology [52].

Comparing the prediction results of RJDT with ITS data allows you to identify possible errors in the registration of raw data. However, in most cases, the reason for the desynchronization is the inaccuracy of the RJDT predictions. This is due to the use of standard or average values of the duration of the operations of the transportation process. We propose to include a simulation model training unit in the RJDT with an ITS integration model. This block can be built using various methods, ranging from the simplest statistical methods, for example, moving averages, to neural networks and methods for analyzing large Big Data. The result of RJDT training will be a reduction in the number and value of deviations of the predicted data from the actual. Finally, the third block of the proposed integration model is the decision support block. Solutions in RJDT terms are adjustments to operational rules by changing the composition and sequence of operations in the flow diagram work of the rail yard. Decisions can be made by humans or by optimization algorithms, with subsequent confirmation by the decision maker. However, a universal solution is the implementation in this module of the algorithm for comparing runs of the simulation model for alternative solutions. The built-in support for Reinforcement Learning [53], [54], as well as the ability to interactively change the parameters of the simulation model with subsequent visual comparison of the results (Compare Runs), also speaks in favor of choosing the AnyLogic simulation tool. These capabilities accelerate the implementation of training and decision support units

and help reduce the cost of integrating digital twins into existing intelligent transport systems.

3.4. Interface

The RJDT interface should provide operational control, adjustment, and planning of the transportation process at all levels of management of the railway junction. We propose to include three blocks in the structure of the RJDT interface to implement operational control.

The control unit visualizes the transportation process. The transportation process is visualized in the form of various graphs and indicators (Fig. 4, 5), and in the form of a dynamic two-dimensional (Fig. 6) or three-dimensional presentation of the work of an individual rail yard or an entire railway junction.

The block for adjusting the transportation process visualizes the queue of operations of the transportation process, and allows you to change the composition, parameters, and sequence of these operations. The result of the adjustment can be immediately implemented by issuing the appropriate commands to the lower levels of management. In addition, this block allows dispatchers, if accidents or shutdowns, to interactively block the availability or operability of individual devices in the model.

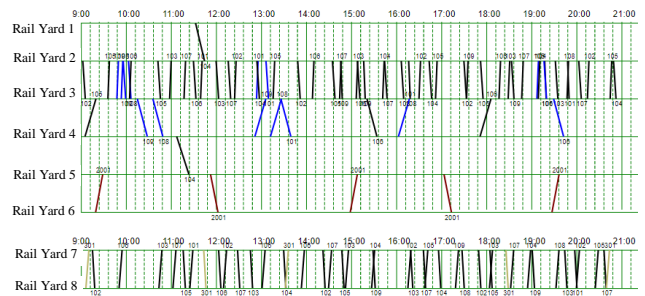


Fig. 4 Train schedule in digital twin (fragment)

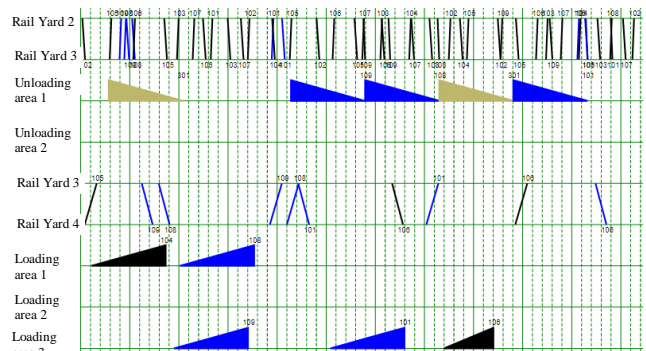


Fig. 5 Rail yard operating schedule in digital twin (fragment)

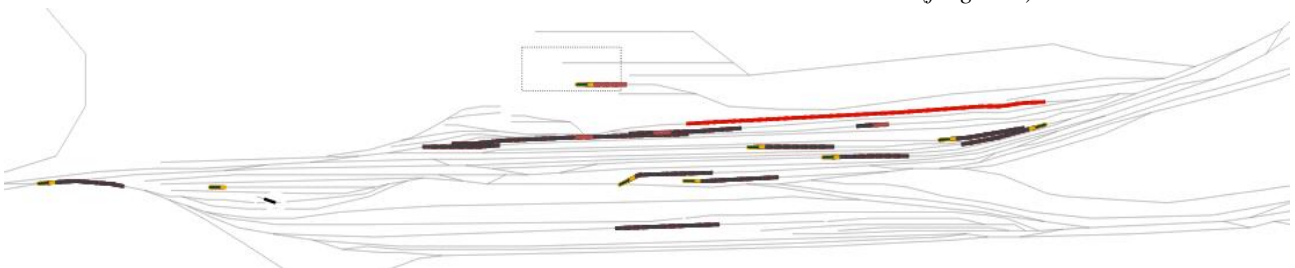


Fig. 6 Screenshot of 2D presentation of digital twin operation (separate rail yard)

The operational planning unit implements an algorithm for comparing runs of the simulation model. The composition of the queue of operations of the transportation process is the main source data of each run. The algorithm used in the block for adjusting the transportation process determines the parameters of the runs. However, the digital twin does not transfer the new parameters to the real control system but uses them as initial data for runs. This block provides dispatchers with the ability to select one or more indicators to be compared during the simulation run. The digital twin transfers the variant of the queue of operations selected by the dispatcher to the block for adjusting the transportation process for implementation.

4 CONCLUSION

Formation of the theory of digital twins of rail yards and junctions is at an early stage. This is mainly due to the complexity of synchronizing real stochastic processes with model ones.

Analysis of existing specialized and universal tools for simulation modeling of railway transport allows us to talk about the advantages of universal tools. This is due both to the high-quality, in most cases, support of these tools by the manufacturer, and to the implementation in them of various tools to support decisions, including, for example, optimization and artificial intelligentsia tools.

The choice of the universal AnyLogic simulation tool in this study is due to the possibility of combining the discrete-event and agent-based paradigms within one simulation model. This allows simulating multi-level management models – from the rail track topology level to the level of train scheduling and distribution of empty cars throughout the railway junction.

We proposed a three-layer RJDT architecture that includes rail track topology, rail junction rules, and an integration model with an ITS.

The mechanism of synchronization of real stochastic processes with model ones is shown. In addition, a method is presented for using the proposed architecture to support management decisions.

REFERENCES

1. Ghobakhloo, M., Fathi, M., Iranmanesh, M., Maroufkhani, P., Morales, M.E., 2021, *Industry 4.0 ten years on: A bibliometric and systematic review of concepts, sustainability value drivers, and success determinants*, Journal of Cleaner Production (302), pp. 127052.
2. Sahal, R., Alsamhi, S.H., Brown, K.N., O'Shea, D., McCarthy, C., Guizani, M., 2021, *Blockchain-Empowered Digital Twins Collaboration: Smart Transportation Use Case*, Machines, 9(9), pp. 193.
3. Fuller, A., Fan, Z., Day, C., Barlow, C., 2020, *Digital Twin: Enabling Technologies, Challenges and Open Research*, IEEE Access (8), pp. 108952–108971.
4. Pouryousef, H., Lautala, P., White, T., 2015, *Railroad capacity tools and methodologies in the U.S. and Europe*, J. Mod. Transport., 1(23), pp. 30–42.
5. Pachl, J., 2018, *Railway operation and control*, VTD Rail Pub, Mountlake Terrace WA, 302 p.
6. Wagg, D.J., Worden, K., Barthorpe, R.J., Gardner, P., 2020, *Digital Twins: State-of-the-Art and Future Directions for Modeling and Simulation in Engineering Dynamics Applications*, ASCE-ASME J Risk and Uncert in Engrg Sys Part B Mech Engrg, 3(6).
7. *RTC - Rail Traffic Controller*, <https://berkeleysimulation.com/rtc.php> (last access: 02.09.2021).
8. *RailSys® Software Suite*, <https://www.rmcon-int.de/railsys-en/railsys-suite/> (last access: 02.09.2021).
9. Medeossi, G., Fabris, S. de, 2018, *Simulation of Rail Operations, Handbook of Optimization in the Railway Industry*, Proc. International Series in Operations Research & Management Science, Springer International Publishing, Cham, pp. 1–24.
10. *OpenTrack Railway Technology*, <http://www.opentrack.ch/> (last access: 02.09.2021).
11. *SYSTRA's RAILSIM X® Software Suite*, https://www.systracanada.com/IMG/pdf/systra_brochure_railsim_x.pdf (last access: 02.09.2021).
12. *ISTRA-System for automated construction of railway station's and junction's simulation models*, <http://trans-expert.ru/istra> (last access: 03.09.2021).
13. Nikitin, A., Groshev, V., 2016, *Automatisation of Control of Station Technological Process Operation in Real Time*, Proceedings of Petersburg Transport University, 2(13), pp. 229–238.
14. Mancera, A., Bruckman, D., Weidmann, U., 2015, *Single Wagonload Production Schemes Improvements Using GüterSim (Agent-based Simulation Tool)*, Transportation Research Procedia (10), pp. 615–624.
15. Novotny, R., Kavicka A., 2016, *Scalable simulation models of railway traffic, 28th European Modeling and Simulation Symposium, EMSS 2016*, Genova, pp. 25–31.
16. Gély, L., Dessagne, G., Pesneau, P., Vanderbeck, F., 2010, *A multi scalable model based on a connexity graph representation*, Computers in Railways XII, Proc. WIT Transactions on The Built Environment, WIT PressSouthampton, UK, pp. 193–204.
17. Shabelnikov, A.N., Olgezyer, I.A., 2020, *Technology and Mathematical Basis of Digital Twin Creation in Railway Infrastructure, Proceedings of the Fourth International Scientific Conference "Intelligent Information Technologies for Industry" (IITI'19)*, Proc. Advances in Intelligent Systems and Computing, Springer International Publishing, Cham, pp. 688–695.
18. He, S., Song, R., Chaudhry, S.S., 2003, *An integrated dispatching model for rail yards operations*, Computers & Operations Research, 7(30), pp. 939–966.
19. Nash, A., Huerlimann, D., 2004, *Railroad simulation using OpenTrack*, Computers in Railways IX, WIT Press, Southampton, pp. 45–54.
20. Middelkoop, A.D., Loeve, L., 06272006, *Simulation of traffic management with FRISO*, Computers in

- Railways X, WIT Press, Southampton, UK, pp. 501–509.
21. Lin, E., Cheng, C., 2009 - 2009, *YardSim: A rail yard simulation framework and its implementation in a major railroad in the U.S.*, *Proceedings of the 2009 Winter Simulation Conference (WSC)*, IEEE, pp. 2532–2541.
 22. Huang, Y., Seck, M.D., Verbraeck, A., 2015, *Component-based light-rail modeling in discrete event systems specification (DEVSS)*, *SIMULATION*, 12(91), pp. 1027–1051.
 23. Wang, X., Rong, L., 10092013, *Marshalling Yard Simulation Based on BP Neural Network Model*, *ICTE 2013*, American Society of Civil Engineers, Reston, VA, pp. 1117–1122.
 24. Roungas, B., Meijer, S., Verbraeck, A., 2018, *Validity of railway microscopic simulations under the microscope: two case studies*, *IJSSE*, 4(8), pp. 346.
 25. Baugher, R.W., 2015, *Simulation of Yard and Terminal Operations*, *Handbook of Operations Research Applications at Railroads*, Proc. International Series in Operations Research & Management Science, Springer US, Boston, MA, pp. 219–242.
 26. Villon simulation tool, <https://www.simcon.sk/en/tools> (last access: 02.09.2021).
 27. Adamko, N., Kavicka, A., Klima, V., 2007, *Agent based simulation of transportation logistic systems*, *DAAAM International Scientific Book 2007*, DAAAM International Publishing, pp. 407–422.
 28. Licciardello, R., Adamko, N., Deleplanque, S., Hosteins, P., Liu, R., Pellegrini, P., Peterson, A., Wahlborg, M., Zatko, M., 2020, *Integrating yards, network and optimisation models towards real-time rail freight yard operations*, *Ingegneria Ferroviaria*, 6(75), pp. 417–447.
 29. *Optimised Real-time Yard and Network Management. D 4.2 Yard simulation software for WP6*, <https://projects.shift2rail.org/download.aspx?id=ac5f4396-3841-4825-bfbb-4bcb4f91eb55> (last access: 02.09.2021).
 30. *AnyLogic Simulation Software*, <https://www.anylogic.com> (last access: 02.09.2021).
 31. Lyubchenko, A., Bartosh, S., Kopytov, E., Shiler, A., Kildibekov, A., 2017, *AnyLogic-Based Discrete Event Simulation Model of Railway Junction*, *Cybernetics and Mathematics Applications in Intelligent Systems*, Proc. Advances in Intelligent Systems and Computing, Springer International Publishing, Cham, pp. 141–149.
 32. Marinov, M., Viegas, J., 2009, *A simulation modelling methodology for evaluating flat-shunted yard operations*, *Simulation Modelling Practice and Theory*, 6(17), pp. 1106–1129.
 33. Borodin, A., Kozlov, P., Kolokolnikov, V., Osokin, O., 2020, *Construction of Efficient Railway Operating Domains Based on a Simulation Examination*, *VIII International Scientific Siberian Transport Forum*, Proc. Advances in Intelligent Systems and Computing, Springer International Publishing, Cham, pp. 1143–1151.
 34. Marinov, M., Şahin, İ., Ricci, S., Vasic-Franklin, G., 2013, *Railway operations, time-tabling and control*, *Research in Transportation Economics*, 1(41), pp. 59–75.
 35. *Arena Simulation Software*, <https://www.rockwellautomation.com/en-us/products/software/arena-simulation.html> (last access: 02.09.2021).
 36. *Plant Simulation*, <https://www.plm.automation.siemens.com/global/en/products/manufacturing-planning/plant-simulation-throughput-optimization.html> (last access: 02.09.2021).
 37. *FlexSim 3D Simulation Modeling and Analysis Software*, <https://www.flexsim.com/> (last access: 02.09.2021).
 38. Cenani, Ş., 2021, *Emergence and complexity in agent-based modeling: Review of state-of-the-art research*, *Journal of Computational Design*, 2(2), pp. 1–24.
 39. Abar, S., Theodoropoulos, G.K., Lemariniere, P., O'Hare, G.M., 2017, *Agent Based Modelling and Simulation tools: A review of the state-of-art software*, *Computer Science Review* (24), pp. 13–33.
 40. Schedit, M., 2018, *Proposal for a Railway Layer Model*, *Computers in Railways XVI : Railway Engineering Design and Operation*, Proc. WIT Transactions on The Built Environment, WIT Press Southampton UK, pp. 157–168.
 41. Woroniuk, C., Marinov, M., 2013, *Simulation modelling to analyse the current level of utilisation of sections along a rail route*, *Journal of Transport Literature*, 2(7), pp. 235–252.
 42. Rakhmangulov, A.N., Mishkurov, P.N., 2012, *Special aspects of railroad station working method simulation model development within AnyLogic system*, *Scientific papers SWorld*, 4(2), pp. 7–13.
 43. *Rail Library webinar: case studies, library elements, and AI*, https://www.youtube.com/watch?v=RVeeqZ99wx0&ab_channel=AnyLogic (last access: 05.09.2021).
 44. Sutton, R.S., Barto, A.G., 2018, *Reinforcement learning: An introduction / Richard S. Sutton and Andrew G. Barto*, Adaptive computation and machine learning, The MIT Press, Cambridge, Massachusetts, 526 p.
 45. Montigel, M., 1992, *Formal Representation of Track Topologies by Double Vertex Graphs*, *Computers in Railways III*, Washington, DC, pp. 359–370.
 46. Shekhar, S., Singh, A., Belur, M.N., Rangaraj, N., 2019, *Development of a railway junction simulator for evaluation of control strategies and capacity utilization optimization*, *2019 Fifth Indian Control Conference (ICC)*, IEEE, pp. 260–265.
 47. Gillet, B.E., Miller, L.E., Johnson, J.G., 1979, *Vehicle dispatching — Sweep algorithm and extensions*, *Disaggregation*, Springer Netherlands, Dordrecht, pp. 471–483.
 8. Rakhmangulov, A., Kolga, A., Osintsev, N., Stolpovskikh, I., Sladkowski, A., 2014, *Mathematical model of optimal empty rail car distribution at railway transport nodes*, *Transport Problems*, 3(9), pp. 125–132.

9. Rakhmangulov, A., Osintsev, N., Muravev, D., Legusov, A., 2019, *An Optimal Management Model for Empty Freight Railcars in Transport Nodes*, Oper. Res. Eng. Sci. Theor. Appl., 1(2).
50. Trofimov S.V., Rakhmangulov A.N., 2000, *The choice of methods for operational management of industrial transport systems*, Nosov Magnitogorsk State Technical University, Magnitogorsk, 145 p.
51. Rakhmangulov, A., Śladkowski, A., Osintsev, N., 2016, *Design of an ITS for Industrial Enterprises, Intelligent Transportation Systems – Problems and Perspectives*, Proc. Studies in Systems, Decision and Control, Springer International Publishing, Cham, pp. 161–215.
52. Rakhmangulov, A.N., Kornilov, S.N., Antonov A.N., 2014, *Device Selection for Identification and Positioning of Railcars for Industrial Environments*, Modern Problems of Russian Transport Complex, 1(4), pp. 16–20.
53. *Training AI-agents with Microsoft Project Bonsai*, <https://www.anylogic.com/features/artificial-intelligence/microsoft-bonsai/> (last access: 10.09.2021).
54. *Boost Performance over Your Baseline with Pathmind AI*, <https://www.anylogic.com/features/artificial-intelligence/pathmind/> (last access: 10.09.2021).

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