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Posted Date: 14 December 2023

doi: 10.20944/preprints202312.1055.v1

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Article

Method and Algorithm of Spatial-Temporal Graph Formation for Dynamic Transportation System [†]

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[†] The study was supported by the Russian Science Foundation (RSF) Grant No. 23-11-00164: <https://rscf.ru/en/project/23-11-00164/>.

Abstract: The real-time Railway Traffic Management Problem (rtRTMP) is discussed in the field of railway transportation. In this paper, rtRTMP is considered for planning shunting routes based on the use of routing methods on a spatial-temporal graph. An approach and algorithm of Spatial-Temporal Graph formation for rail yard transportation network is proposed. The idea is to construct an undirected loop-free Double Vertex Graph for determining optimal shunting routes consisting of several half-runs for several trains shunting under draw-out tracks capacity constraints. Experimental results on the rail yard simulation model are presented.

Keywords: spatial-temporal graph; rail yard; dynamic transportation system; shunting operations; shunting route; double vertex graph; simulation; rail yard

1. Introduction

Traditionally, elements of transportation infrastructure can be described by an abstract graph. The main direction of using graph theory in solving transportation problems is the routing of object movement in a closed system. A well-known mathematical proof of graph theory is the issue of the seven bridges of Königsberg [1]. The issue is whether it is possible to cross all seven bridges in the city of Königsberg in one walk, crossing each bridge exactly once. It is known that graph formation and graph processing are vast areas of mathematics, and there are many techniques for creating graph networks [2]. However, the use of traditional techniques for constructing the transportation routing graph of a railway station is limited by several criteria on which the parameters of shunting operations depend. In this paper, we propose a technique for generating the transportation network of a railway station to optimize the shunting route.

2. Literature Review

Traditionally, the problem of routing the movement of objects is based on solving the problem of determining the shortest distance between origin and destination points [3]. However, in practice, the parameters of vertices and edges of the transportation network change in time. A solution to this issue was first proposed in 1969 [4]. In his study, Dreyfus suggested an approach to generate routes at a given start time of objects based on the use of the FIFO (first-in first-out) principle. There are many tools for finding the shortest distance on graphs, such as route planning on the Internet, car navigation system, logistics optimization, modeling of railway transport and urban traffic [5]. The shortest path search issue is a classical combinatorial optimization issue, and there are many algorithms currently available to solve it [6]. For example, such classical graph routing algorithms as Clarke and Wright algorithm [7], Mole and Jameson algorithm [8], Christofides-Mingoizzi and Toth sequential insertion algorithm [9], sweep algorithm [10, 11, 12].

In the 1990s, the routing problem on a transportation network was considered based on determining the minimum travel time of an object at the optimal moments of travel start time and arrival time. Orda and Rom [12], as well as many others [14, 15, 16, 17, 18, 19] considered this issue

in a discrete formulation. However, because of using this approach, an increase in the number of vertices of the transportation network with expected object delay locations is observed in the operational planning of object routes [20]. If we exclude the FIFO principle and limit the delay time of an object in a vertex of the graph, its routes may contain an infinite number of edges, which in turn does not satisfy the optimality criterion [21]. Therefore, the solution of the Capacitated Vehicle Routing Problem (CVRP) is considered NP-hard. Most of the algorithms proposed to solve the routing problem on a transportation network are based on heuristic and metaheuristics [22]. In the field of mathematics, on the one hand, the most effective of the published algorithms are: repeated local search with separation of solution sets (ILS-SP) [23], knowledge-based local search (KGLS) [24], hybrid genetic search (HGS) [25], Slack Induction by String Removals (SISR) [26] and fast localized ILS optimization (FILO) [27].

However, under the conditions of implementation of the concept of “total control” by companies, the importance of making operational decisions on the organization and management of traffic flows has increased, and as a consequence, the application of the presented algorithms at a low level of abstraction (more details) is observed. More accurate methods for solving the routing problem on the graph [28, 29] based on the improvement of discrete optimization of system operation have been proposed. New approaches have been suggested for solving the routing issue, for example, based on the use of the method of branches and bounds [30, 31], mathematical programming [32, 33, 34] and dynamic optimization [35]. At the same time, the methods of transportation network graph formation are improved, which consider the specifics of individual modes of transportation and the functioning of transport infrastructure objects.

The real-time Railway Traffic Management Problem (rtRTMP) is actively discussed in the field of railway transportation. RtRTMP is the problem of detecting and solving time-overlapping conflicting requests made by multiple trains on the same track resources. It typically consists in taking retiring, reordering or rerouting train actions in such a way that the propagation of disturbances in the railway network is minimized. Integer linear programming algorithms are being improved, e.g., for selecting the train route for daily planning of freight trains [36]. Modern mathematical models and algorithms of train routing in railway transport hubs based on the use of dynamic programming method are proposed [37, 38, 39]. Algorithms of route pre-processing for each individual train are improved based on the use of ant colony optimization to form a flexible train schedule between rail yards [40]. The presented universal models have found their application in the design of railway transport nodes and stations, informatization of the tactical level of management and automation of solutions of design and planning tasks in railway transport. We suggest the integrated use of the method of simulation modeling and methods of optimization of traffic schedule, planning of train routes in the railway transport hub [38, 39, 41, 35, 42, 43], train processing at the railway station [44], infrastructure and transport network [45]. In this case, the traditional graph representation, where rail yards are used as vertices and edges as interchange spans, is used as a tool for transportation network formation. RtRTMP рассматривается при планировании shunting route на основе использования методов маршрутизации на графе. Совершенствуются алгоритмы маршрутизации, предлагается макро моделирование технологии работы железнодорожных станции [37, 46, 47, 48]. Отличительной особенностью исследований является описание транспортной сети, в которой вершинами являются группы railway switch или yard, рёбрами – station track. При этом рассмотренный подход не позволяет оптимизировать низкоуровневые операции по выбору оптимальных shunting route, состоящих из нескольких half-run.

For conditions of lower abstraction level, two groups of methods of forming graph rail yard are distinguished:

1. A separate railway switch is described in the graph as a vertex.
2. A separate railway switch is described in the graph in the form of edges.
3. A combined description of track rail yard sections.

The methods of the first group include the method of describing the railroad infrastructure by a simple directed graph [49]. However, such a representation of the transportation network does not

solve the problem of changing the train direction, and the authors propose to solve this problem at a higher level of logic of the mathematical model. The idea of using Double Vertex Graphs to describe railroad track development was first proposed [50]. The use of the graph presented by the author makes it possible to determine the optimal routes of train traffic at a railway station with a complex scheme of track development.

The methods of the second group emphasize the way of representing station tracks in the form of one or more vertices of a graph [51], and such representation of rail yard transportation network is of practical importance for station tracks occupancy management.

The methods of the third group are oriented on combining the presented methods of the first and second groups, based on constructing Double Vertex Graphs and allocation of railway track circuit sections into vertices according to the equivalence classes [50]. The presented methods have found their application in specialized programs for building simulation models of railway transport. This allowed to consider low-level optimization on shunting route formation, while considering several fundamental constraints related to the change of train direction and route signaling system.

The accuracy and versatility of graph-based routing methods can be improved, for example, when using sweep algorithm on Double Vertex Graphs for the representation of the railway track [52, 53], the logic of the algorithm for determining the optimal route based on tracking and determining the direction of movement at each iteration for an individual train relative to the switches that limit the track, when the capacity of the draw-out track is limited.

The paper proposes a method of forming Double Vertex Graphs for implementing routing algorithms in complex shunting operations consisting of several half-runs.

3. Railyard routing graph

The transportation network of a railway station is proposed to be described by a connected oriented vector graph with a set of railway switch and railway track connected to each other in accordance with the track development scheme.

The optimal train route through the transportation network can be calculated using various methods [54]. We propose to use a fast heuristic "sweep algorithm" for transportation routing [10], the idea of which is based on the sequential verification of the condition for each i -th vertex of the graph

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

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

Vertex i is included in the optimal route only if condition (1) is satisfied. This algorithm allows finding all optimal routes from one or more initial vertices of the transportation network to all other vertices.

3.1. Traditional routing graph

Let $G(P, L)$ be an undirected graph of regular form. For example, Figure 2 shows the diagram of a switchboard represented in the form of an undirected graph G . The edges of the graph are characterized by initial P_i , final P_j vertices and length L_{ij} . Train movement from vertex 1 to vertex 4 is performed along the route R1, which consists of two half-trips. The first half-trip is performed along the route $\{1; 2; 3\}$. Then there is a change of direction and the train travels along the route $\{3; 2; 4\}$. However, the route from vertex 3 to vertex 4 is not included in the optimal route R2 in case the track development scheme is described by a traditional undirected graph. In the table of optimal routes (Figure 1), the value of λ_i is equal to the number of the vertex that precedes the i -th vertex, and $L\lambda_i, i$ is the length of the edge between vertices λ_i and i .

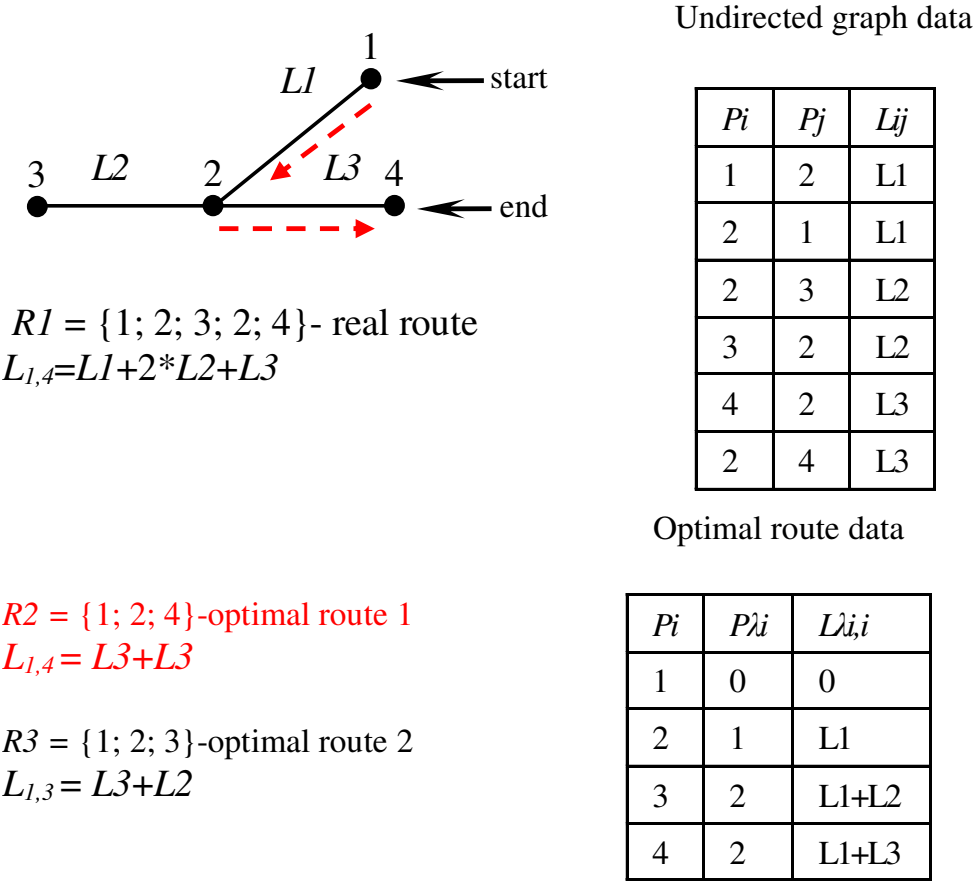


Figure 1. Traditional way of describing a railway switch as part of a routing graph.

Thus, the search for an optimal route from node 1 to node 4 using the traditional approach will result in an erroneous train route. Such a description of the track development scheme graph does not allow planning and optimizing complex train routes through the railway station and shunting operations with changes in train direction.

3.2. Double Vertex Graphs for the representation of the raylway track

Double Vertex Graph $D(G, P_0)$ consists of a regular graph G and a bijective mapping of the set of vertices onto itself “0” called the joining mapping [1], with each vertex having one duplicate, a vertex cannot exist alone. Two vertices forming a pair are called joined vertices.

Figure 2 shows an example of a Double Vertex Graph. The edges of the graph are characterized by initial P_i, P_{i0} final P_j, P_{j0} vertices and length L_{ij} . The movement of a train from vertex 1 to vertex 4 is performed along the route $R1$, which consists of two half-trips. The first half-trip is performed along the route $\{50; 10; 20; 30\}$. Then a change of direction occurs and the train travels along the route $\{3; 2; 4; 4; 6\}$. In this case, the “Path rule” applies before the train starts moving, it must move to the vertex duplicate P_i, P_{i0} , then start its movement along the edge L_{ij} [50]. The use of this rule allows tracking the direction of the train’s movement and exclude its angular arrival when forming a route. For example, a train that starts its movement at vertex (5) should move to the right, while a train that starts its movement at vertex (5⁰) should move to the left.

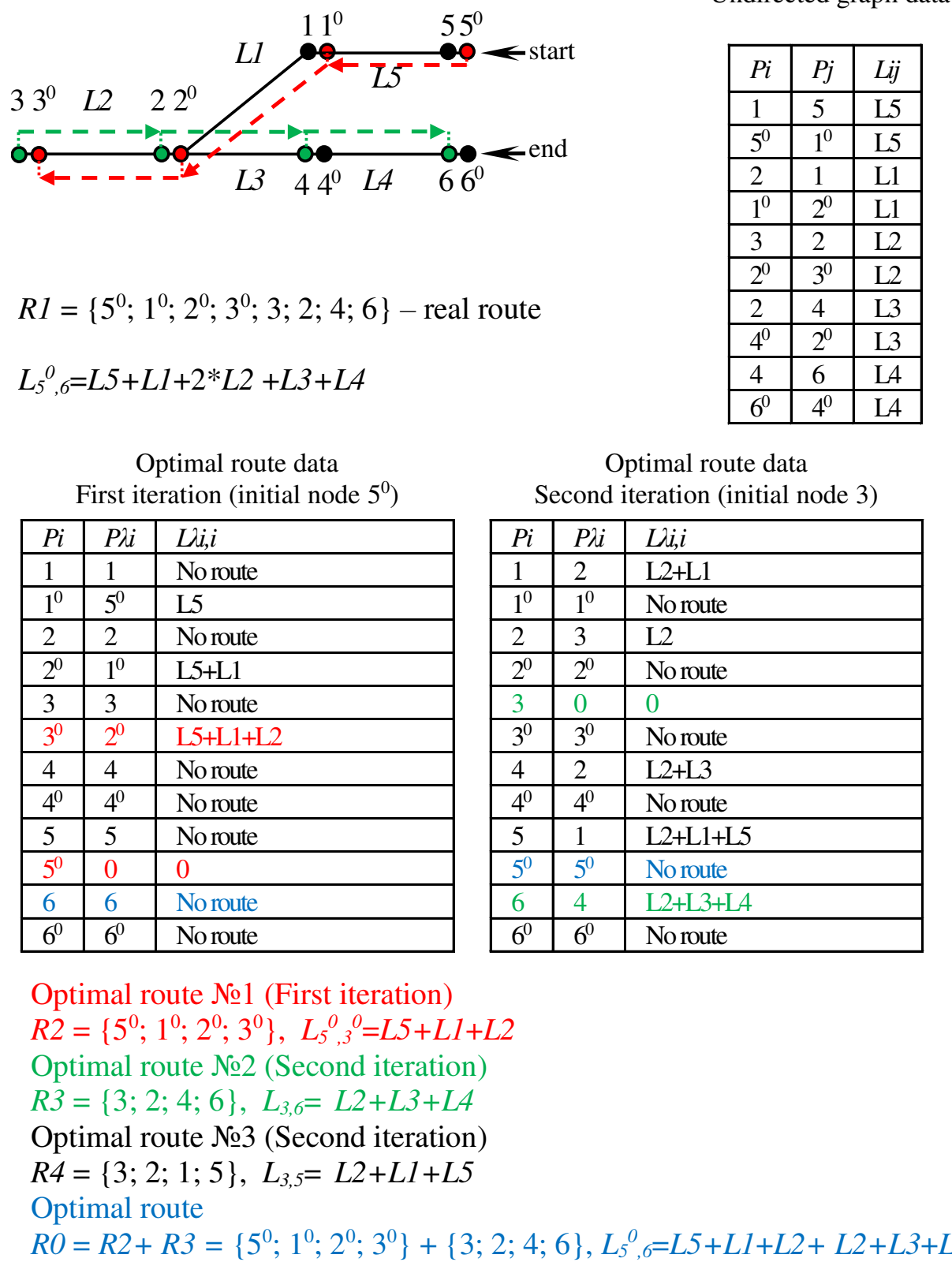
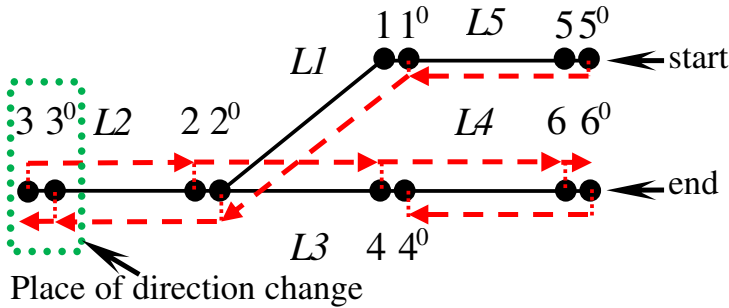


Figure 2. Double Vertex Graph for the representation of the railway track.

However, the route from vertex 3 to vertex 6 is not included in the optimal route $R2$ in this case, it is necessary to perform the second iteration with a new set of initial vertices, Figure 2 shows the initial vertex for the second iteration – (3).

Let us consider variants of determining the optimal route, which includes a draw-out track for changing the direction of the train. Suppose that vertices (3) and (30) are identified as the place where the train stops to change its direction (Figures 3 and 4), this case can be represented by two variants.

Variant 1: Optimal route of train shunting on Double Vertex Graph in case of identifying the place of changing the direction of train movement when the final vertices are not known (Figure 3).



$R1 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 4; 6\}$ – real route

$L5^0_{,6}=L5+L1+2*L2 +L3+L4$

$R2 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 4; 6; 6^0, 4^0\}$ –
optimal route №1
 $L5^0_{,6}=L5+L1+2*L2 +L3+0+L4$

$R3 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 1; 5\}$ –
optimal route №2
 $L5^0_{,5}= L5+L1+2*L2+L1+L5$

Undirected graph data

P_i	P_j	L_{ij}
1	5	L5
5 ⁰	1 ⁰	L5
2	1	L1
1 ⁰	2 ⁰	L1
3	2	L2
2 ⁰	3 ⁰	L2
2	4	L3
4 ⁰	2 ⁰	L3
4	6	L4
6 ⁰	4 ⁰	L4

Optimal routes data

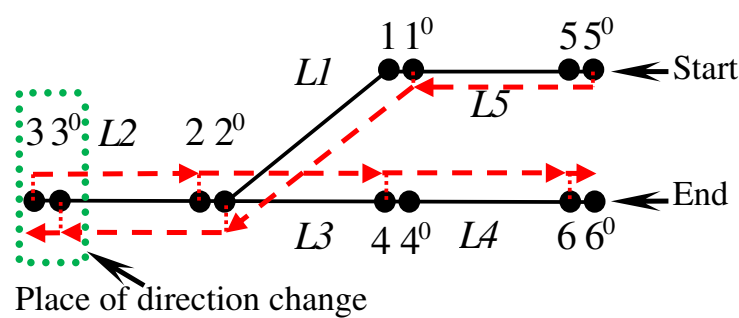
P_i	$P_{\lambda i}$	$L_{\lambda i}$
1	2	$L5+2*L1+2*L2+L3+L4$
1 ⁰	5 ⁰	L5
2	3	$L5+L1+2*L2$
2 ⁰	1 ⁰	$L5+L1$
3	3 ⁰	$L5+L1+L2+0$
3 ⁰	2 ⁰	$L5+L1+L2$
4	2	$L5+L1+2*L2+L3$
4 ⁰	6 ⁰	$L5+L1+2*L2+L3+2*L4+0$
5	1	$2*L5+2*L1+2*L2+L3+L4$
5 ⁰	0	0
6	4	$L5+L1+2*L2+L3+L4$
6 ⁰	6	$L5+L1+2*L2+L3+L4+0$

Figure 3. Option #1 for optimal route train shunting on Double Vertex Graph.

Figure 3 shows that the route from vertex 5 to vertex 6 is part of the optimal route R2, with vertices (5) and (4⁰) being the final vertices.

Option #2. Optimal route of train shunting on Double Vertex Graph in case of identification of the place of train direction change at known end vertices (5; 1; 4⁰; 6⁰) (Figure 4).

The considered variants can potentially be used in the formation of shunting routes consisting of several half-runs. However, the choice of train stop location is a dynamic variable that depends on the length of an individual train and the capacity of the track section. For example, because of the sweep algorithm, train shunting routes do not include draw-out tracks. This is due to the specifics of marshaling and shunting operations. If a shunting route consists of several half-runs, it is necessary to use draw-out tracks.



$R1 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 4; 6\}$ – real route

$L_{5^0,6^0}=L5+L1+2*L2 +L3+L4$

$R2 = \{5^0; 5\}$ – optimal route №1
 $L_{5^0,5^0}=0$

$R3 = \{5^0; 1^0; 1\}$ – optimal route №2
 $L_{5^0,1^0}=L5+0$

$R4 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 4; 4^0\}$ –
Optimal route №3
 $L_{5^0,4^0}= L5+L1+2*L2+L3+0$

$R5 = \{5^0; 1^0; 2^0; 3^0; 3; 2; 4; 6; 6^0\}$ –optimal
route №4

$L_{5^0,6^0}= L5+L1+2*L2+L3+L4+0$

Undirected graph data

P_i	P_j	L_{ij}
1	5	L5
5 ⁰	1 ⁰	L5
2	1	L1
1 ⁰	2 ⁰	L1
3	2	L2
2 ⁰	3 ⁰	L2
2	4	L3
4 ⁰	2 ⁰	L3
4	6	L4
6 ⁰	4 ⁰	L4

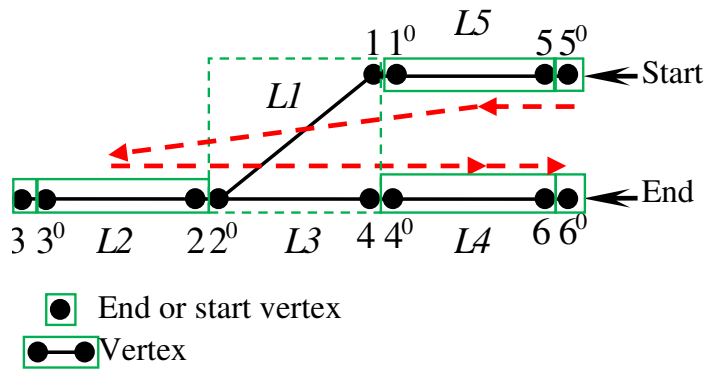
Optimal routes data

P_i	$P_{\lambda i}$	$L_{\lambda i,i}$
1	1 ⁰	L5+0
1 ⁰	5 ⁰	L5
2	3	L5+L1+2*L2
2 ⁰	1 ⁰	L5+L1
3	3 ⁰	L5+L1+L2+0
3 ⁰	2 ⁰	L5+L1+L2
4	2	L5+L1+2*L2+L3
4 ⁰	4	L5+L1+2*L2+L3 +0
5	5 ⁰	0
5 ⁰	0	0
6	4	L5+L1+2*L2+L3+L4
6 ⁰	6	L5+L1+2*L2+L3+L4+0

Figure 4. Option #2 for optimal route train shunting on Double Vertex Graph.

3.3. Connectivity graph for the representation of the railway track train shunting

Let $G(P, L)$ be an undirected non-looped connectivity graph. The edges of the graph are characterized by initial P_i , final P_j vertices and length L_{ij} . The train movement from vertex (5^0) to vertex (6^0) is performed along the route $R1$, which consists of two half-trips (Figure 5). The first half flight is performed along the route $\{(5^0); (5,1^0); (2,3^0)\}$. Then there is a change of direction and the train travels along the route $\{(2,3^0); (4^0,6); (6^0)\}$.



$R1 = \{(5^0); (5,1^0); (2,3^0); (4^0,6); (6^0)\}$ – real route

$$L_{5^0,6^0} = L1 + L3$$

$R2 = R1 = \{(5^0); (5,1^0); (2,3^0); (4^0,6); (6^0)\}$ – optimal route №1

$$L_{5^0,6^0} = L1 + L3 + 0$$

$R3 = \{(5^0); (5,1^0); (2,3^0); (3)\}$ – optimal route №2

$$L_{5^0,3} = L1 + 0$$

Undirected graph dat

P_i	P_j	L_{ij}
5^0	$5,1^0$	0
$5,1^0$	5^0	0
$2,3^0$	$5,1^0$	L1
$5,1^0$	$2,3^0$	L1
$2,3^0$	3	0
3	$2,3^0$	0
$2,3^0$	$4^0,6$	L3
$4^0,6$	$2,3^0$	L3
$4^0,6$	6^0	0
6^0	$4^0,6$	0

Optimal routs data

P_i	$P_{\lambda i}$	$L_{\lambda i}$
5^0	0	0
$1^0,5$	5^0	0
$2,3^0$	$1^0,5$	L1
3	$2,3^0$	L1+0
$4^0,6$	$2,3^0$	L1+L3
6^0	$4^0,6$	L1+L3+0

Figure 5. Connectivity graph for the representation of the railway track train shunting.

The convexity graph considered in Figure 5 connectivity graph can potentially be used in forming a shunting route consisting of several half-runs. When using the connectivity graph, it is necessary to consider the length of an individual train when it stops at a vertex, e.g., vertex $(3^0,2)$ with capacity $L2$. Often there are cases when a shunting train goes beyond a traffic light and stops at several minor railroad tracks.

3.4. Proposed Double Vertex Graphs for representation of the draw-out track

The approach we have developed is based on Double Vertex Graph. The idea is to construct undirected loop-free Double Vertex Graphs $D(G, V^0)$ to determine optimal shunting routes consisting of multiple half-runs for multiple train shunting under draw-out track capacity constraints. Each vertex of the graph – a shunting track – is matched with two vertices – a “real” and a “virtual” vertex, e.g., real vertex 2 and virtual vertex 2^0 (Figure 6).

The virtual vertex is connected to the main railroad track of the switch and the virtual edge $(2,3)$. As a result of this transformation, the optimal route $R1 = \{1; 2^0; 3; 2; 4\}$ is formed.

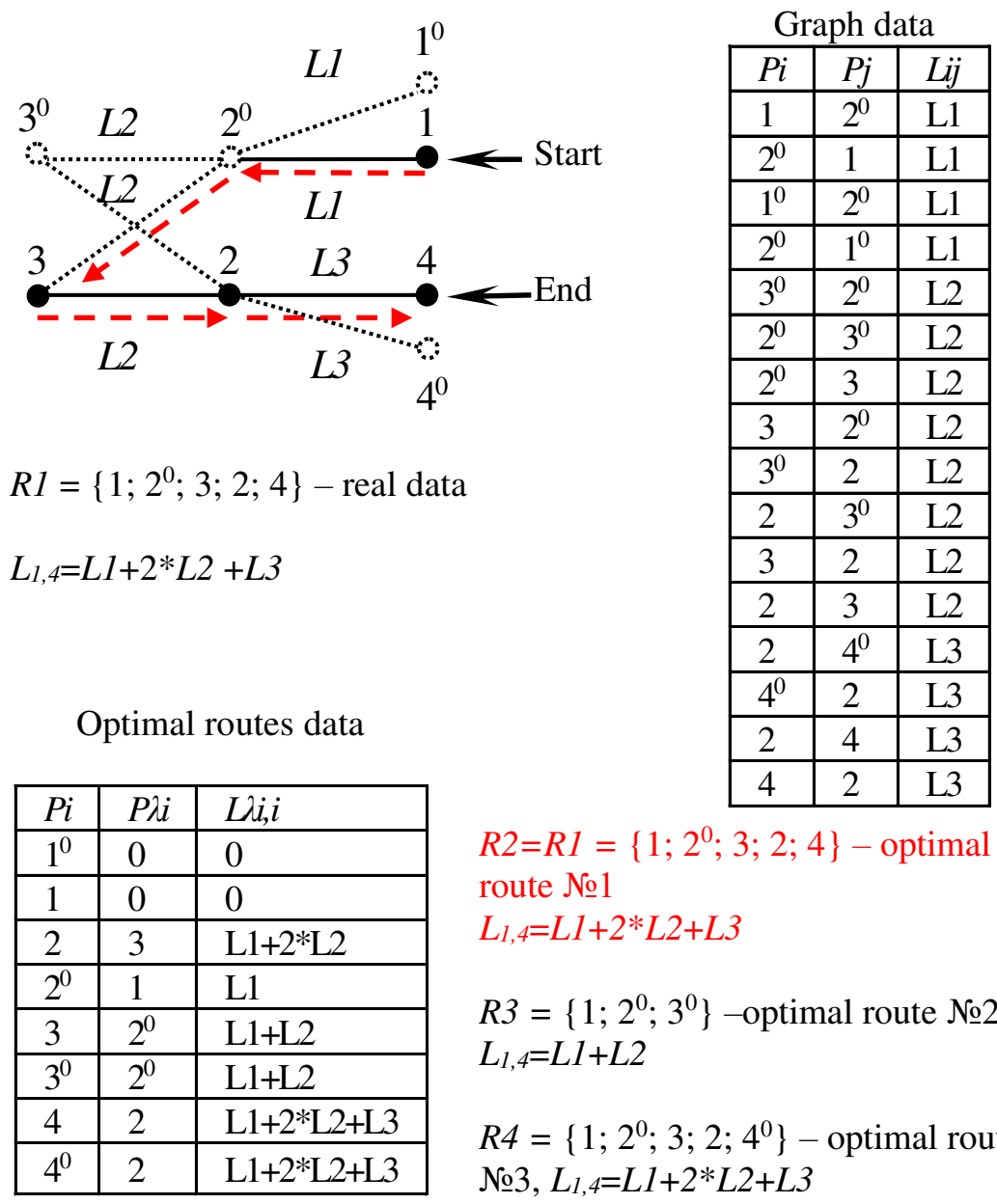


Figure 6. Proposed Double Vertex Graphs for representation of the draw-out track.

With this graph representation, the use of the “Path rule” to track the direction of train shunting will not be required. The direction of train shunting is determined automatically, depending on the generated optimal shunting route [55].

4. Algorithm of forming railyard transport network

In turn, the routing results of the proposed Double Vertex Graph rail yard are the initial data for optimization of train shunting priorities by comparing the indicators of their routes.

For the practical use of the proposed approach to the formation of Double Vertex Graph rail yard in solving the problems of routing rolling stock, an algorithm of forming rail yard transport network has been developed (Figure 7) and the concepts of “main”, “excluded” and “alternative” railway track have been introduced. The outgoing railroad tracks of a railroad switch include tracks both forming and not forming an acute angle with each other. One of the railroad tracks that create an acute angle with each other is not included in the graph description, such a track is called “excluded”, the other track is called “alternative”. The railroad track that does not create an acute

angle with “excluded” and “alternative” is called “main”. In this case, the rule applies: the “excluded” track for one switch is the “excluded” track for the other.

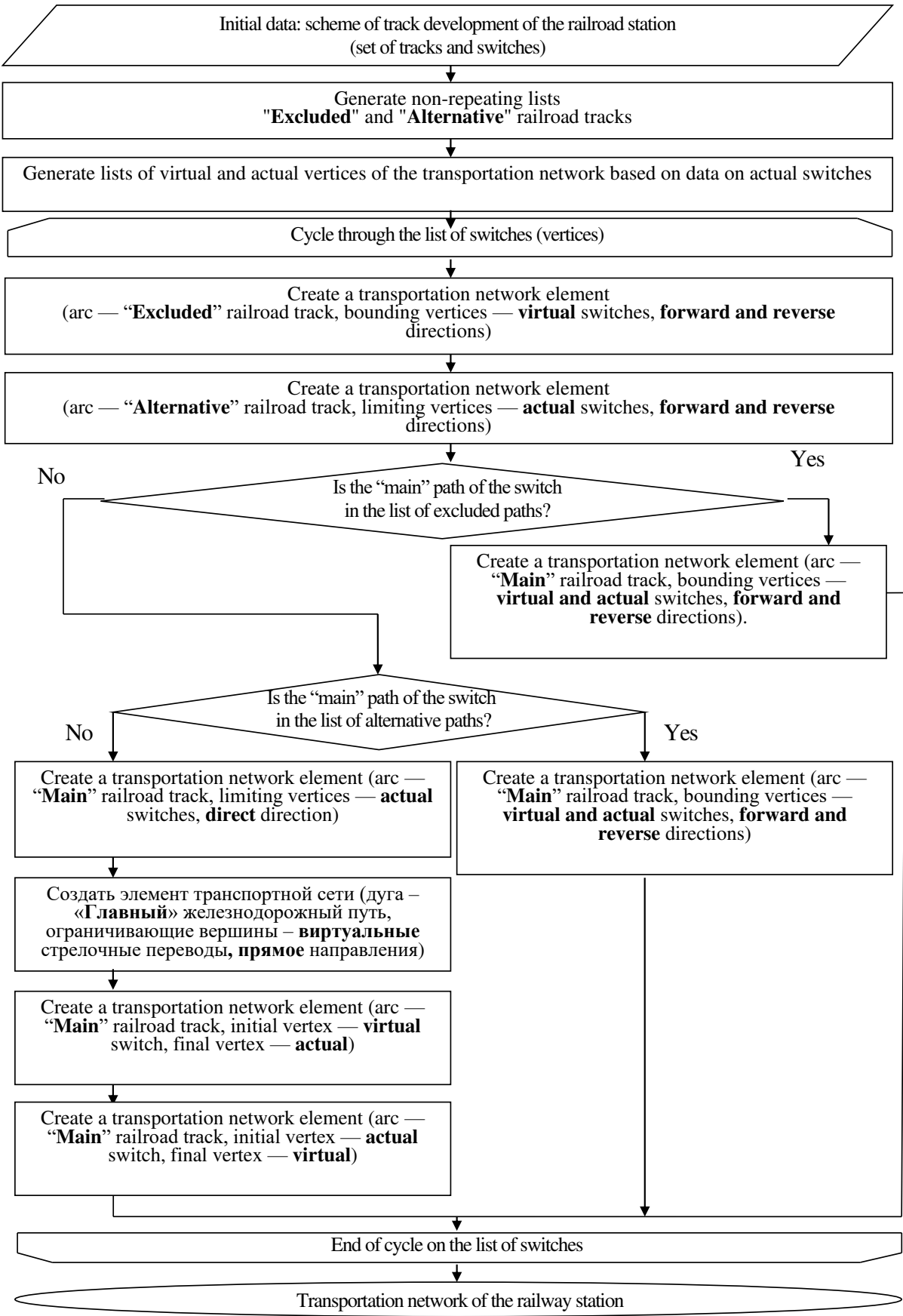


Figure 7. Algorithm of forming railyard transport network.

5. Simulation experiment

5.1. Description of the test object

To evaluate the adequacy of the proposed Double Vertex Graph rail yard with the draw-out track and Algorithm of forming rail yard transportation network, a simulation model of the railway station operation was built on the example of an industrial marshalling yard (Figure 8). The list of track development of industrial marshalling yard is presented in Table 1.



Figure 8. Fragment Industrial marshalling yard.

Table 1. Краткая ведомость путевого развития.

Destination railway track	Number of railway tracks
Receiving-and-departure tracks	7
Draw-out track	8
Loading-unloading tracks	44
Straight branch line	19
Station-to-station block	4
Railway switch	115
Diamond crossing with slips	1

AnyLogic development environment [56, 57, 58] was used as a software tool for simulation modeling. The simulation model was built based on the joint use of discrete event and agent-based approaches within a single model [58]. The use of several approaches in building a simulation model of a railway station allowed to implement a “sweep algorithm” to search for optimal shunting routes on the proposed transportation network, as well as to implement a mechanism of coordinated interaction of shunting trains.

5.2. Simulation results

Схема путевого развития Industrial marshalling yard добавлена в имитационную модель на основе использования файла формата Shape, из геоинформационной системы предприятия (Figure 9). Это позволило использовать фактические длины как основных, так и дополнительных путей, например connecting tracks.

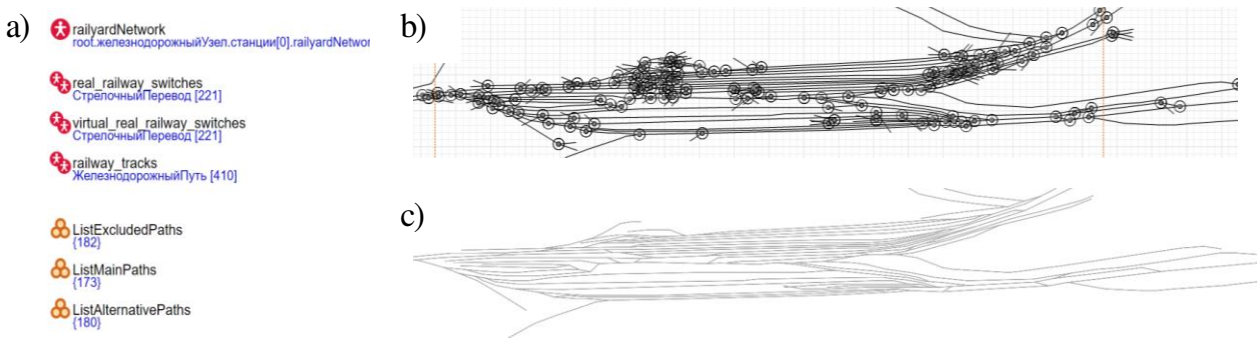


Figure 9. Фрагмент схемы путевого развития в имитационной модели. а) объекты транспортной сети; б) схема станции в модели; в) схема станции при запуске эксперимента.

It should be noted that to consider the lengths of railway sidings / dead-end sidings (dead-end path) when forming a closed graph, bounding vertices are mapped to each such path, and in addition, clearance points are placed. Therefore, the number of elements of the agent population “real_railway_switches” and “railway_tracks” differs from the list of railway tracks (Table 1).

The results of the conducted experiments on the built simulation model showed the principal features of formation of both Double Vertex Graph rail yard with the draw-out track, and the route of railroad rolling stock movement on the rail yard transportation network. For example, in case of detection of capacity limitation at any draw-out track, it is searched and replaced by a track of necessary capacity, and a part of the route to the new draw-out track is redefined. The result of the adjustment is a route, the list of edges of which includes the railway exhaust tracks or the list of consecutive straight branch lines with sufficient capacity to change the direction of movement of the railroad train. Therefore, the built simulation model used the “sweep algorithm” redefined on railroad tracks to search for optimal routes of rolling stock movement along the proposed transportation network of the railway station (Figure 10).

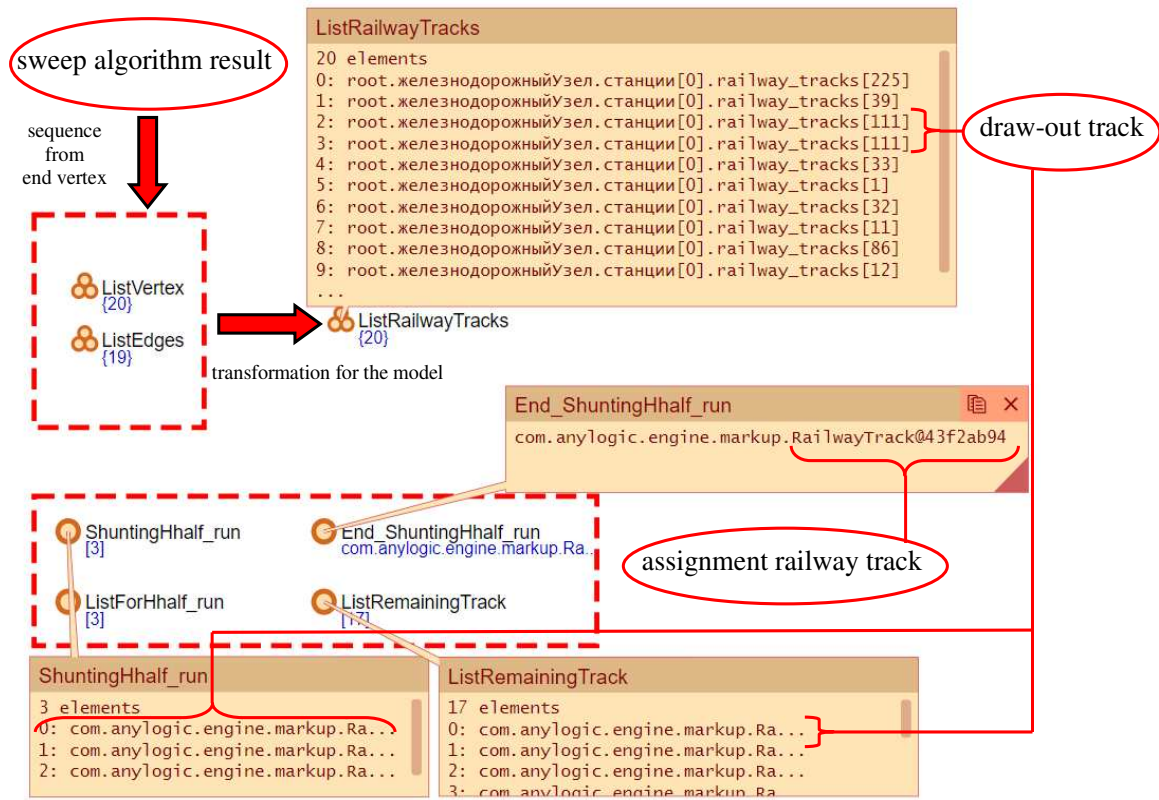
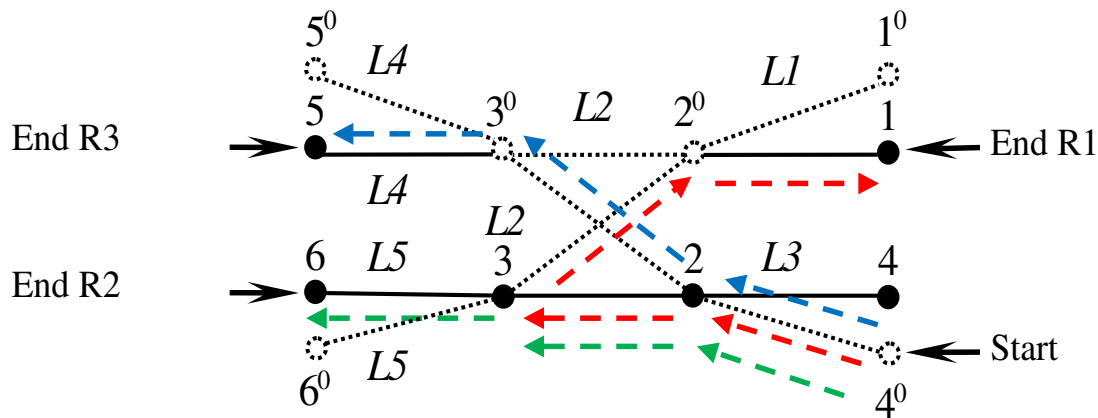


Figure 10. «Sweep algorithm» result для отдельного поезда в имитационной модели.

Two variants of transportation network formation depending on symmetry of railroad tracks exclusion are revealed.

Option 1: Shunting route at consecutive or combined arrangement of parks, where symmetric exclusion of railroad tracks (edges) is observed (Figures 11 and 12).

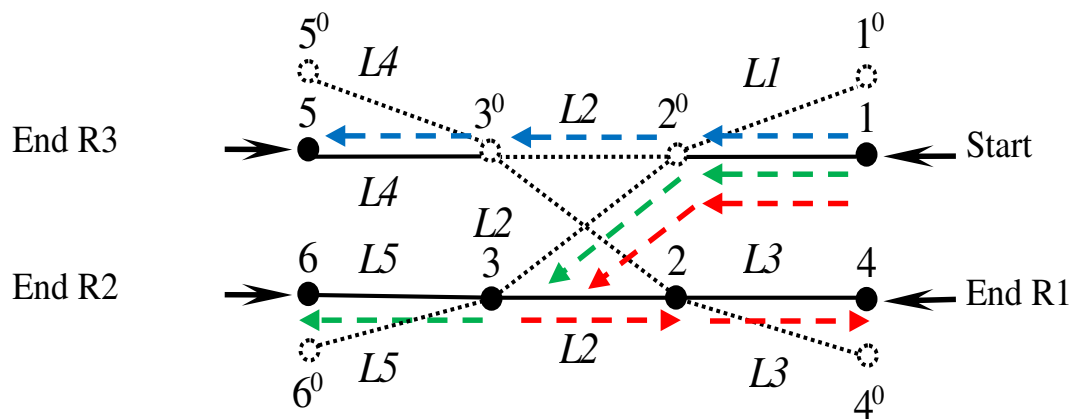


$$R1 = \{4^0; 2; 3; 2^0; 1\}, L_{4,1}^0 = L3 + 2 * L2 + L1$$

$$R2 = \{4^0; 2; 3; 6\}, L_{4,6}^0 = L3 + L2 + L5$$

$$R3 = \{4^0; 2; 3^0; 5\}, L_{4,5}^0 = L3 + L2 + L4$$

Figure 11. Scheme of shunting route with symmetric exclusion of railroad tracks (edges), where the start of train shunting is the “alternative” track (2;4⁰).



$$R1 = \{1; 2^0; 3; 2; 4\}, L_{1,4} = L1 + 2 * L2 + L3$$

$$R2 = \{1; 2^0; 3; 6\}, L_{1,6} = L1 + L2 + L5$$

$$R2 = \{1; 2^0; 3^0; 5\}, L_{1,5} = L1 + L2 + L4$$

Figure 12. Scheme of shunting route with symmetric exclusion of railroad tracks (edges), where the beginning of train movement is the “excluded” track (2⁰;1).

Option 2. Shunting route at sequential or combined arrangement of parks, where there is asymmetric exclusion of railroad tracks (edges) (Figures 13 and 14).

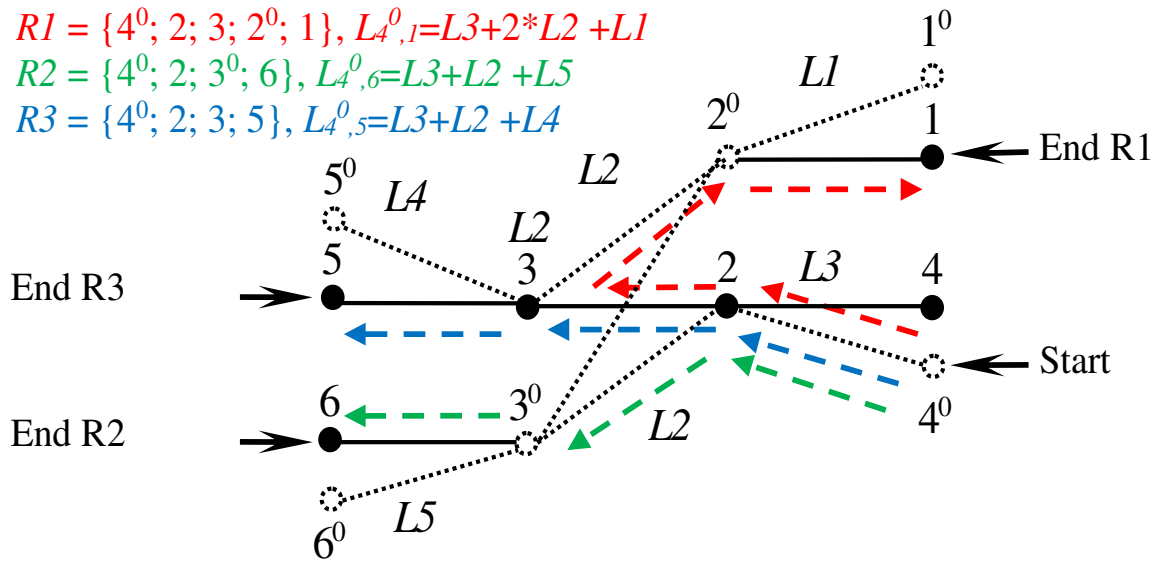


Figure 13. Scheme of shunting route at asymmetric exclusion of railroad tracks (edges), where the beginning of train shunting is the “alternative” track (2;4⁰).

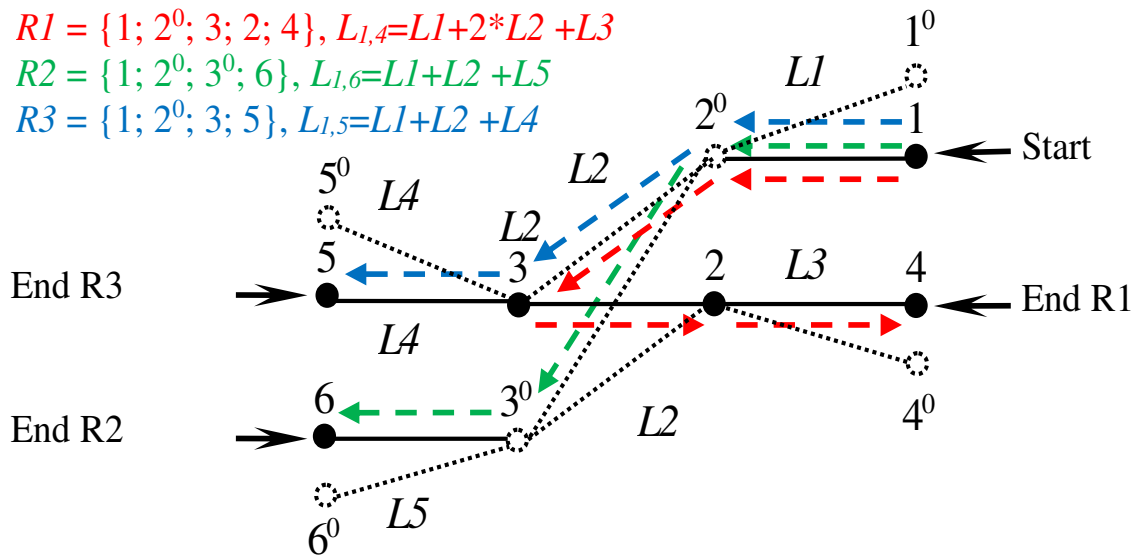


Figure 14. Scheme of shunting route at asymmetric exclusion of railroad tracks (edges), where the beginning of train movement is the “excluded” track (2;1).

Thus, the results of the conducted experiments on the simulation model show the adaptability of using the proposed Double Vertex Graphs for representation of the draw-out track when solving the problem of optimization of transportation at the railway station. It should be noted that the adaptability is achieved based on using the developed algorithm of forming rail yard transportation network. In this case, according to the results of using the “sweep algorithm”, routes are formed for individual shunting trains, which include a draw-out track or a list of consecutive straight branch lines with sufficient capacity to change the direction of movement of the railroad train.

6. Conclusion

Nowadays, there are many algorithms for solving the routing problem on graphs. In the field of railway transportation, the considered algorithms are actively used to solve the real-time Railway Traffic Management Problem. The adaptability of such algorithms is achieved by using sufficiently developed ways of representing the railway transportation network at high levels of abstraction, for example, individual rail yards are used as vertices of the graph, and edges — distances.

The analysis of existing specialized methods of graph formation and routing methods on graphs for railway transportation allows us to speak about the advantages of specialized Double Vertex Graphs of transportation routing for a lower level of abstraction, for the level of railway station. This is due to the increased adaptability of using different routing algorithms on graphs in the conditions of planning complex shunting operations on rail yard.

The method of forming rail yard transport network proposed in the paper extends the adaptability of using routing algorithms on graphs for rail yard conditions based on complex use of the developed method of forming Double Vertex Graphs for representation of the draw-out track and algorithm of forming rail yard transport network, which is confirmed by the results of experiments on the simulation model of rail yard in AnyLogic environment. At present, the authors implement the developed method of creating a rail yard transport network within the framework of the information transport system of an industrial enterprise.

Future research aims to evaluate the effectiveness of using the proposed rail yard transport network as input data in the digital rail yard twin, and for spatio-temporal optimization.

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