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Construction of a cable yarding track by mathematical and software methods

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Abstract. Constraining factors for the development of traditional solutions for the development of hard-to-reach logging areas are given. Mathematical and software methods are proposed to calculate the construction of routes for rope-trailer installations. Methods of solving the problem of laying an acceptable optimal route using discrete programming methods under conditions of risk and uncertainty are proposed. On a practical example in typical natural and industrial conditions of the North-West Federal District of the Russian Federation (sq.4 v.39 of the Primorsky district forestry of the Kurortny forestry of St. Petersburg) the construction of a mathematical model for solving the stochastic problem with quantile indices is carried out.

1 Introduction

Under the conditions of the new economic reality [1], traditional solutions based on multi-operational forest machines, working on the Scandinavian sorting technology of timber harvesting, based on feller-buncher and bucking machine on a wheeled or caterpillar engine and wheeled sorting picker [1] for the development of hard-to-reach forest areas have become difficult to apply or not applicable for a number of factors [1]. It is worth noting the existing domestic solutions from other resource industries based on all-terrain snowmobiles to overcome the tyranny of alternatives, but at the moment the production capacity of snowmobile equipment manufacturers is focused on solving problems to meet the needs of the oil and gas industry [2].

Given the industry's need for simple traditional solutions with low operating costs and undemanding personnel qualifications, along with roperail roads [3] and narrow gauge railroads, rope skidding is one of the most promising methods of wood transportation at logging sites with difficult natural and production conditions [4-6]. One of the most labor-intensive operations of rope skidding is installation of the installation. During clear-cutting, the harvesting area is developed by fan method in order to reduce the number of movements of the main rig.

When using an advanced type of rope skidding rig with an articulated carriage [7-9], due to the possibility of making turns, it is possible to develop forest areas of complex

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shape, including those intended for thinning. In this case, there is a need to choose the direction of fibers, their length and quantity.

2 Materials and methods

It is necessary to be guided by the optimality criteria set by the development manager or decision maker in the selection issues.

The task is to lay the optimal rope route for the technology of forest harvesting with the use of rope installations with a rotated route in the plan.

Obtaining scientifically justified solutions using program methods is an important component in the design of technological process of harvesting areas development. The theory of optimal solutions can be applied to the problems of route selection [10-26].

The main task in solving the problem of laying the optimal rope route is to build a model of decision making in conditions of risk and uncertainty of the production process. In this case, the purpose of the study is a quantitative justification of optimal solutions using the methods of analysis, mathematical modeling and programming. In this case will be set sets of acceptable conditions, in the form of angles of rotation of the route, which can not be violated. The minimum number of angles and their values are an indicator of efficiency, allowing to compare different solutions in terms of efficiency.

3 Problem statement

The task of constructing an optimal route is uncertain, since the decision maker is not aware of the probability of each of the physical states of the information field.

To solve the problem using program methods, it is necessary to create a mathematical model of building an optimal path from point A (SCR location), passing through intermediate pivoting supports and capturing the necessary zones of plot development, ending at the point of final support (B).

Such basic problems have been posed many times in the literature, so back in the 1960s basic algorithms for solving optimal path finding problems were developed [13, 14]. Algorithms for finding the shortest path (or the path of least cost) between two vertices have long been of great interest in various industries, including logistics, the design of linear objects (gas pipelines, roads and railroads), the defense industry, etc. [15-17]. Currently, the most advanced practical developments in this area are possessed by programmers of computer games [18-28]. Information on this issue, in accordance with the specifics of the profession, can be found on various professional forums, and is rarely published in scientific publications.

However, when constructing a route under uncertainty, the task becomes much more complicated. Therefore, for its solution it is necessary to address to modern research of mathematicians in this direction.

Mathematical methods are universal, but for their application it is necessary to correctly set the problem, which requires taking into account the specific features of the system under study.

Problem formulation is an essential and responsible stage influencing the choice of a solution method. It can be divided into several consecutive stages:

1. Establishing the boundary of the system to be optimized, i.e., representation of the system in the form of some isolated part of the real world. In our case, the working space is the forest area designated for harvesting, and it may also include access roads. The forest area can be initially divided into apiaries, within which the routing will be considered. However, it is more rational to use an integrated approach, because, due to the technical

possibility of making turns, it is possible to create the whole scheme of harvesting area development using program methods.

2 Determination of the performance indicator on the basis of which the characteristics of the system can be evaluated. Which in the case of SCR routing is the labor intensity of routing, which significantly reduces the overall performance of the technology. The extreme value of the system performance indicator corresponds to the best option.

3. Selection of intra-system independent variables, which should adequately describe the conditions of system functioning, i.e., maximize the model's approximation to the real process by taking into account additional constraint functions. The applicability of the model will eventually be revealed by practice.

4. Building a model that describes the relationships between the variables of the problem and reflects the influence of independent variables on the value of the performance indicator. The process of building the system is the most labor-intensive and requires a clear understanding of the specific features of the system under consideration.

4 Solution method selection

There are several basic methods for solving optimization problems, but not all of them are suitable for choosing the optimal route. Universal and the most elementary from the point of view of understanding is the method of complete enumeration, but its application is limited to integer programming problems with a small number of variables and a narrow area of boundary conditions. It is of little use in solving practical problems [10].

To choose a solution method, it is necessary to describe the characteristic features of the optimal SCR routing problem:

1. Represents an n-step decision making process;

2. is defined for any number of steps and has a structure independent of them;

3. The parameters describing the state of optimality of the system, independent of the number of steps, are set.

To solve problems with the above features, we apply the method of dynamic programming [11].

Let us describe the algorithm of solving problems by the method of dynamic programming:

1. We select parameters characterizing the state s of the controlled system before each step.

2. Break the operation into steps.

3. Determine the set of step controls u_i for each step and the constraints imposed on them.

4. Determine what gain is given at the i step of the control u_i, if the system was in state s before, i.e. we write down the gain function:

$$W_i = f_i(s, u_i) \quad (1)$$

5. We determine how the state s of system S will change under the influence of control u_i at step i, it is transited to a new state:

$$s' = \phi_i(s, u_i) \quad (2)$$

6. We write the basic recurrence equation of dynamic programming, expressing the conditional optimal gain:

$$W_i(s) = max\ (f_i(s, u_i) + \ W_i + 1(\phi_i(s, u_i))) \quad (3)$$

7. We perform conditional optimization of the last m steps given a set of states s from which it is possible to reach the final state in one step, calculating for each of them the conditional optimal gain $Wm(s)=max(f_m(s,u_i))$, and find the conditional optimal control $u_m(s)$, for which this maximum is achieved.

8. We perform conditional optimization *(m-1)* of step 6 of the algorithm, plagarizing in it $i=(m-1),(m-2),\ldots$ and for each of these steps we specify the conditional optimal control $u_i(s)$, at which the maximum of the function is reached. At the first step the state of the system does not vary:

$$W^* = W_1(s_0) \tag{4}$$

9. We perform unconditional optimization of the control, reading the corresponding recommendations at each step: we take the control found optimal at the first step $u_1{}^*=u_1(s_0)$; change the state of the system according to step 6; for the newly found state we find the optimal control at the second step $u_2{}^*$ etc. until the end of the process.

There is an alternative method of enumeration. Algorithm $A*$ is an ordered search algorithm, in which the evaluation function is used

$$\hat{f}(n) = \hat{g}(n) + \hat{h}(n) \tag{5}$$

where: $\hat{h}$ is heuristic function, $g(n) = k(s, n)$ – cost of the optimal path from the initial vertex *s* to some arbitrary vertex *n*.

To evaluate optimality, we assume that each path has a cost, and achieving the minimum cost under the given conditions will be the criterion of optimality. That is, $f(n)$ - is the cost of the optimal path, provided that it passes through vertex *n*. The sum of the actual cost of the optimal path from vertex *n* to any of the target vertices. The lower bound on the cost of a path from a point *S* to a destination point *N* is a straight line. When using the algorithm $A*$, when some vertex is revealed, it turns out that the optimal path to it has already been found.

5 Application of probabilistic method of mathematical modeling

The first stage of obtaining the optimal solution is:

- Establishing the boundary of the system to be optimized, i.e., we select a separate section from the forest area, a harvesting area, on which we need to solve the problem of finding the optimal route; In addition, it is necessary to select isomeric areas in the harvesting area with different characteristics of the stand in terms of density.

- Determination of the efficiency index, i.e., identification of the system characteristic on the basis of which it is possible to identify the best project or a set of the best conditions of the system functioning. In the case of determining the route of the ropeway the most correct technological factor will be the minimum sum of angles of turns of the route. That will provide the maximum speed and stability.

In order to be able to easily describe the constraints caused by the need to maintain the width of the route, we put half of the required width of the route in the diameter of trees (obstacles) that must be bypassed.

The natural distribution of trees obeys Poisson's law. The average distance between trees is a derivative of the completeness of the forest area [12, 19-21]:

$$P_n(k) = \frac{\lambda^k}{k!} exp(-\lambda) \tag{6}$$

here K is a number of events (number of meetings),
λ is a distribution parameter

$$\lambda = \frac{l}{l_{av}} \quad (7)$$

In order to transform a forest area into a mathematical form, it is necessary to create a grid structure from the plot, with a conditionally uniform distribution of trees. In which the average distance between trees l_{av} is the diameter of the inscribed circle. To create an isotropic system, the intersection points of the circles are connected in three/six angles, obtaining the honeycomb model shown in Figure 1.

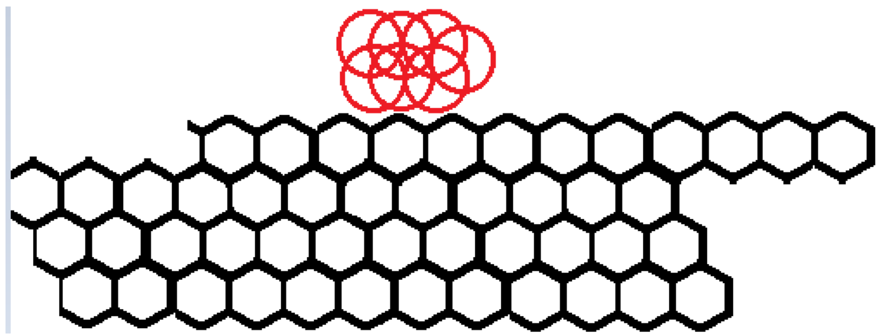

Fig. 1. Cellular cell model.

In case of uneven distribution of trees in the harvesting area, it is divided into clusters. In each cluster, the average distance between trees is set. Since the distance between trees is the size of a cell within one number of meetings, the cell sizes increase by multiples as the allowable number of meetings increases.

In case a part of trees (obstacles) is removed as part of selective felling or sanitary felling, the average distance between trees will increase proportionally to the intensity of felling.

The clarity of this method will be demonstrated by the example of a harvesting area in the quarter 4 of the Primorsky district, Kurortny forestry. The forest area has the status of protective urban forests. In this area it is planned to carry out sanitary and health-improving measures in the form of sanitary thinning. Having curvilinear boundaries of the plot, coinciding with the boundaries of the allotment, we assume the most effective use of a rope skidder with the possibility of turning.

Section 39 of the quarter 4 of the Primorsky district forestry, Kurortny forestry has the following taxation characteristics: area S - 4.5 ha; composition: 6E2Os2B+C; forest type: CW; age 90, 75, 75, 70; grading 1; completeness 0.6; stock 311 m^3; average diameter E - 32; C, B - 28, Os - 36 cm.

The general view of the harvesting area after processing of cartographic and aerial survey data with separation of trees to be cut (triangle) and remaining trees (circle) is shown in Figure 2.

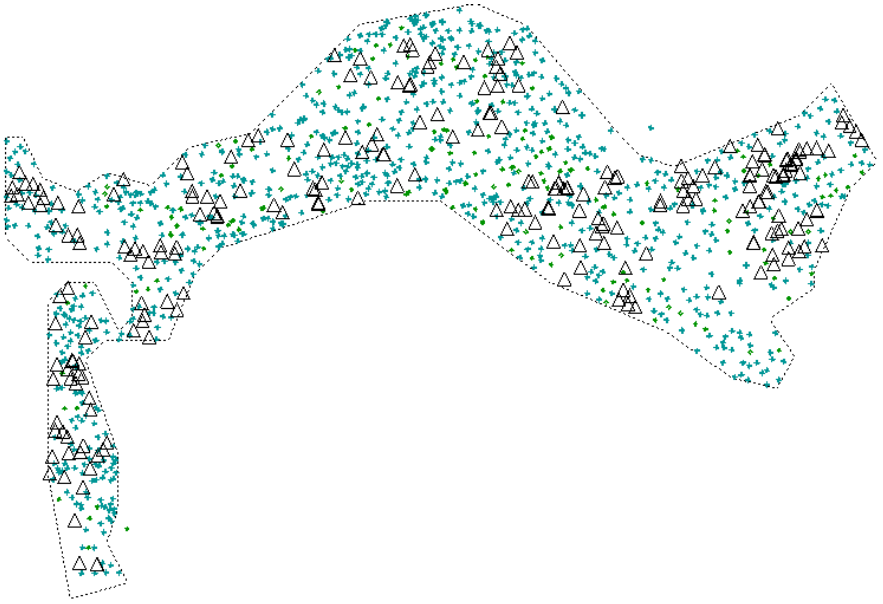

Fig. 2. General view of the cutting area.

To create a cluster model of a harvesting area, it is necessary to determine the basic cell size, i.e., l_{av} is calculated from the area of the cut and the number of trees.

The number of trees *N*, pcs. is determined by the formula

$$N = \frac{Z}{Vd_{av}} \tag{8}$$

where: *N* - number of trees, pcs;

Z - stock, m^3 ;

V_{dav} *is the* volume of one tree of average thickness.

As a result of calculations using formula 8, we obtain the volume , V_d , m^3 , for the rocks: B_{28} - 0.68 m^3 ; C_{28} - 0.68 m^3 ; E_{32} - 0.96 m^3 ; Os_{36} - 1.16 m^3 .

As a result of calculations, we get the value of *N*:

$$N = \frac{311}{0.6*0.96+0.2*1.16+0.2*0.68} = 327$$

pcs/ha

Average tree spacing with homogeneous distribution of trees in an allotment

$$l_{av} = \sqrt{\frac{S}{N}} \tag{9}$$

As a result of calculations, we obtain the value of l_{av}:

$$l_{av} = \sqrt{\frac{10000}{327}} = 5.53$$

m.

In case of selective or sanitary thinning of average intensity 33%, the average distance between trees will proportionally increase 5.53*1.33=7.36. To demonstrate the methodology, we will use the baseline value of the average distance.

Based on the formulas of the tree distribution law (6.7), a diagram of probabilities of the number of meetings with obstacles (trees) at different distances at a fixed value of the average distance (l_{av}=5.53m) is plotted in Figure 3. The data for the diagram is Table 1 of the dependence of probabilities of the number of meetings with obstacles (trees) on different distances at a fixed value of the average distance (l_{av}=5.53m).

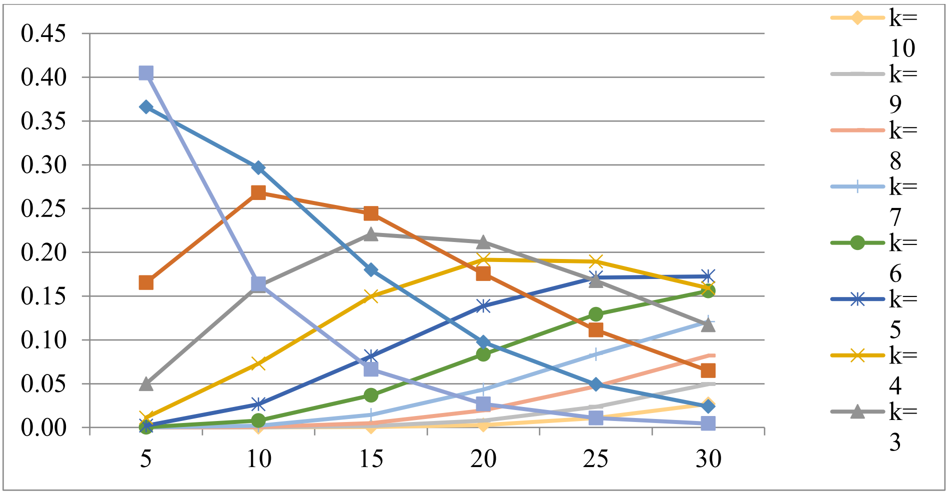

Fig. 3. Probability diagrams of the number of meetings with obstacles (trees) at various distances at a fixed value of the average distance (l_{av}=5.53m).

Where *x-axis* is the length of the rectilinear section, m; *y-axis* is the probability (*p*) of meeting k obstacles.

Table 1. Probabilities of the number of meetings with obstacles (trees) at different distances at a fixed value of the average distance (lav=5.53m).

	Distance between obstacles, m.					
Probability	5	10	15	20	25	30
Pn(k) k=0	0.405	0.164	0.066	0.027	0.011	0.004
Pn(k) k=1	0.366	0.296	0.180	0.097	0.049	0.024
Pn(k) k=2	0.165	0.268	0.244	0.176	0.111	0.065
Pn(k) k=3	0.050	0.162	0.221	0.212	0.168	0.117
Pn(k) k=4	0.011	0.073	0.150	0.192	0.189	0.159
Pn(k) k=5	0.002	0.026	0.081	0.139	0.171	0.172
Pn(k) k=6	0.000	0.008	0.037	0.084	0.129	0.156
Pn(k) k=7	0.000	0.002	0.014	0.043	0.083	0.121
Pn(k) k=8	0.000	0.000	0.005	0.020	0.047	0.082
Pn(k) k=9	0.000	0.000	0.001	0.008	0.024	0.049
Pn(k) k=10	0.000	0.000	0.000	0.003	0.011	0.027

Based on the analysis of the diagrams it follows that at each permissible value of the number of meetings (k=0, 1, 2...) there are peak values of probabilities of such meetings. After reaching the extremum of the function, the graph tends to the minimum values. However, this fact is not decisive for making a decision on the choice of the maximum straight-line distance at any *k* values. For example, the maximum value of probability p(4)=0.19 is reached at a distance of 25 meters. A further decrease in the values of meeting probability refers to the value k=4, while the values of meeting probabilities with k>4 continue to increase. Consequently, practical values have values of the left parts of the graphs before reaching the maximum.

Setting the maximum permissible number of meetings k=10 it is necessary to determine the probabilities of meeting Pn(k)<10 (Figure 4). Calculation of values in Table 2 is based on the expression of the sum of probabilities of events$n \le k \le 10$ at $0 \le n \le 10$

$$P_n(0 \le k \le 10) = \sum_n^{10} p_n - p_n! \qquad (10)$$

Table 2. The probability of the presence of a number of obstacles exceeding the permissible values k.

Probability	Distance between obstacles, m					
	5	10	15	20	25	30
Pn(k) 0≤k≤10	1.000	1.000	1.000	0.999	0.993	0.977
Pn(k) 1≤k≤10	0.595	0.836	0.934	0.972	0.982	0.972
Pn(k) 2≤k≤10	0.229	0.540	0.753	0.875	0.933	0.949
Pn(k) 3≤k≤10	0.064	0.272	0.509	0.699	0.822	0.884
Pn(k) 4≤k≤10	0.014	0.110	0.289	0.487	0.654	0.766
Pn(k) 5≤k≤10	0.002	0.037	0.139	0.295	0.465	0.607
Pn(k) 6≤k≤10	0.000	0.011	0.058	0.157	0.294	0.435
Pn(k) 7≤k≤10	0.000	0.003	0.021	0.073	0.165	0.279
Pn(k) 8≤k≤10	0.000	0.001	0.007	0.030	0.081	0.158
Pn(k) 9≤k≤10	0.000	0.000	0.002	0.011	0.034	0.075

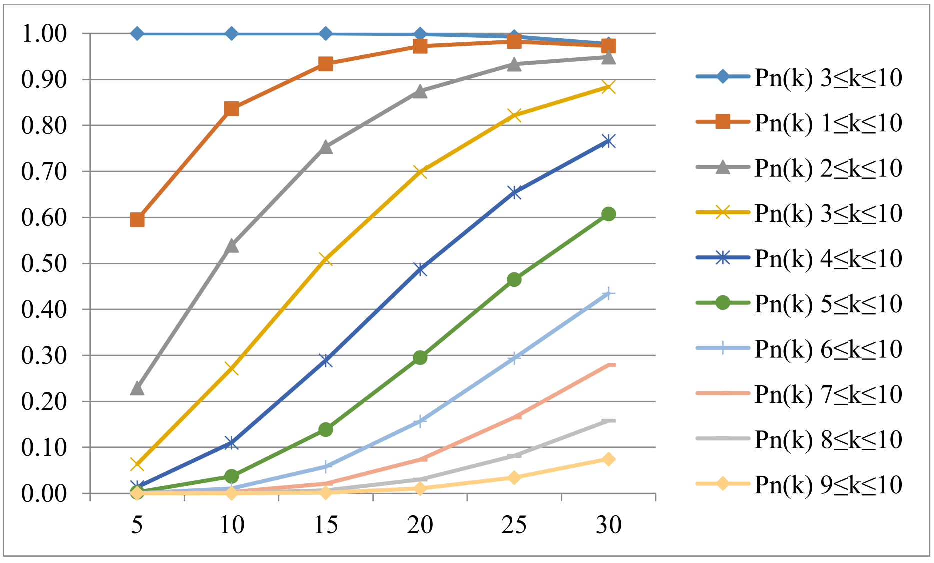

Fig. 4. The total probability of meeting Pn (n k≤≤ 10).

6 Conclusions and recommendations

From the data analysis, it is evident that the probability of n meetings increases with increasing distance.

To determine the optimal distance, an acceptable probability and an acceptable number of meetings must be established.

The number of meetings in route construction will correspond to the number of turns. The maximum number of turns should be set based on economic criteria. The acceptable probability is determined by the decision maker.

As a result of the performed actions, the general view of the harvesting area, on which the route construction takes place, will take the form shown in Figure 5. As the permissible number of meetings increases, the size of cells, on the faces of which the route construction will take place, will increase (Figures 6-8).

Fig. 5. General view of the cutting area with a probability of 1 meeting.

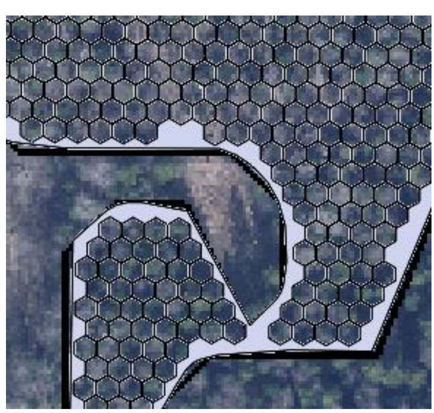

Fig. 6. The probability of meeting 1 tree.

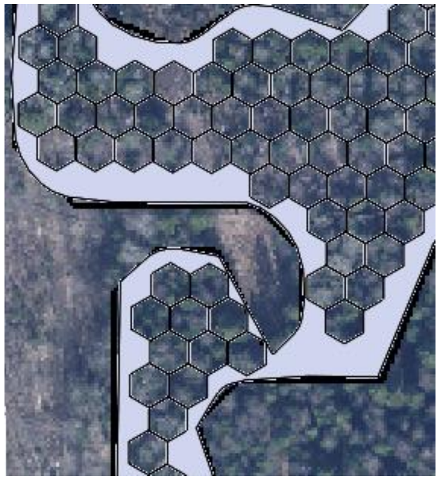

Fig. 7. The probability of meeting 2 trees.

Fig. 8. The probability of meeting 3 trees.

Figures 6-8 show a view of the logging site with a breakdown into cellular structures, assuming that the allowable number of meetings is changed and their probability is maintained.

7 Conclusions and recommendations

In view of the fact that the described process in the part of meeting with trees in the process of laying the route has a random character, i.e., by its characteristics belongs to Markov processes. The assumption of Poisson's law distribution of trees in the forest gives the process static regularity to a random process, i.e., static stability. The random function, is the occurrence of trees and its random value, as well as the value of the probability of its occurrence, is set by us to calculate different variants.

The process of calculation when moving along the route is discrete, the probability of transition to each subsequent state depends only on the previous state and is a process without consequences, i.e., it is a non-return set.

The optimization problem is to find the overall best route and to choose the number of acceptable occurrences in each homogeneous plot. Since the actual distribution of trees in the plot is not homogeneous, but clustered, it is necessary to take into account the difference of non-occurrence lengths when designing the BE route (P=const) along the pre-mapped route (corresponding to the homogeneous model).

At further stages of solving the problem, applying the methods of Markov processes of dynamic programming, the result will be obtained in the form of variants of the optimal route. The calculation methodology and results will be published in further works of the authors.

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