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Theoretical Approaches to Logging Trail Network Planning: Increasing Efficiency of Forest Machines and Reducing Their Negative Impact on Soil and Terrain

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Abstract: A good part of the forest that survived active logging during the previous period of industrialization is now in remote areas: on steep slopes, in waterlogged or permafrost areas. There, especially on the slopes, the use of land disproportionately affects ecological processes, specifically hydrological (e.g., peak waves, suspended load, etc.). Organizing off-trail transport of log timber under such conditions is a challenge associated with specific difficulties. Almost any cutting area has sites of different capacity (stand volume per ha), which require the use of high flotation machines and have habitats that cannot be disturbed. The frequency of trips to cutting areas increases with the stand volume in these areas, but there are areas that machines have to drive round. Areas with weak soils need forest machines to carry less weight or to use additional attachments to hold the load. Unfavourable grades need the bundle to be limited in weight to maintain the tractive effort of a skidder. Because this activity is carried out with a high impact on ecology, it calls for a mathematical model and technique to evaluate logging routes and to assess the impact that logging activities have on the forest soil and subsoil and on the forest in general. This paper is devoted to the creation and justification of such a technique and offers an algorithm for careful forest use and forest-friendly logging.

Key words: Cutting area, soil and subsoil, ecology, environmentally friendly forest exploitation, ecological efficiency.

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Introduction

There is an inexorable growth of both the world population and per capita consumption. All possible efforts should be made to meet human needs in food, feed and building materials by increasing productivity, improving the storage and processing of crops, and also more equitable distribution of essential goods (Hunter et al., 2017; Rockström et al., 2017). These requirements for the intensification of agricultural practices are in conflict with the task of preserving the forest. In cases where arable land on an easily accessible surface is already fully used, the activity will extend to still forested land, including increasingly steep slopes, lands of frozen or swampy soils. Thus, the onset of agricultural land and the increasing demands for intensified land use will also affect forest management practices, making deforestation more intensive in previously inaccessible areas, on slopes in areas of permafrost soils. Slopes, and other difficult or vulnerable terrains affect many physical processes due to the following: Gravitational acceleration (for example, surface water flow rates, energy required for lifting); Geometry (for example, incoming precipitation flows and solar radiation per unit of the earth's surface area, the complexity of land transport routes); Hydrology (the carrying capacity of soils, the ability of soils to withstand repeated loads, etc.); and Land use in the mentioned areas, and especially on the slopes and in the areas of permafrost soils disproportionately affects ecological processes (Masyagina et al., 2019). For example, with increasing inclination angles, the rate of soil erosion and the frequency of mass depletion (i.e., landslides and avalanches) increases, especially after the trees are cut down and the roots linking the soil decay (Horton et al., 2017; Flores et al., 2019).

In assessing the results of the main logging operations, two main aspects can be distinguished: Operational (technological) and ecological efficiency. The first is estimated by such indicators as energy and labour intensity of the process, unit costs (cost price), etc. (Grigoriev, 2006; Grigoriev et al., 2018).

Ecological efficiency will be assessed according to the degree of negative damage to the forest ecosystem. It should be noted that damage to the forest environment during logging could be positive for subsequent natural regeneration (Grigoriev, 2006, 2016). New methods for assessing ecological efficiency for industry (incl. the forest industry) (Grigoriev et al., 2012, 2014) have been developed recently.

With regard to logging production, ecological efficiency might be considered as "a component of the vector of overall efficiency". Thus, the concept of ecological efficiency is inextricably linked to the economic, technical, technological, and other parameters of the entire production process.

In this regard, it is required to develop a method for optimizing the placement of forest machine tracks in terms of reducing energy intensity, along with the cost of the most expensive technological operation of the main logging operations - tree skidding.

Materials and Methods

Practically in any cutting area there are sites of land with different forest reserves per hectare—sites with difficult passability of skidders on soil and terrain conditions, as well as biotopes that have to be driven around (Dobretsov et al., 2016).

It is necessary to make a greater number of trips to areas containing a larger reserve of wood. Some areas have to be driven around. In areas with weakly bearing soils, it is required to limit the weight of the bundle or additionally strengthen the carry. If there are climbs and descents in the cargo direction, it is necessary to limit the weight of the bundle by the tangential force of the skidder (Rudov et al., 2019). Usually, to solve the above problems, the coordinate-volumetric method of tracing the paths of the primary forest transport is used.

The power N of the skidder, necessary for trailing a bundle, depends on the tangential tractive force F_K and the speed V of movement, and is determined by the well known expression (Grigoriev et al., 2013):

$$N = \frac{F_K \cdot V}{\eta_T} \quad (1)$$

where η_T is transmission efficiency.

It should be emphasized that the power of the engine installed on the skidder is known and the machine must operate in the modes when N is close to or equal to N_{nom}. Therefore, for any part of the cutting area, the following condition must be met:

$$F_K \cdot V = N \cdot \eta_T \quad (2)$$

If a skidder with a half-loaded bundle of full-length log has a weight G_T, the fraction k' of the weight of a bundle G_B on itself and moves up (descent) with a certain angle α, then the tangential traction force can be determined approximately from the expression:

$$F_{\text{K}} = G_T(\varphi_{\text{T}} \cos\alpha \pm \sin\alpha) + k'G_{\text{B}}(\varphi_{\text{T}} \cos\alpha \pm \sin\alpha) + (1-k')G_{\text{B}}(\varphi_{\Pi} \cos\alpha \pm \sin\alpha) \quad (3)$$

where φ_{T} and φ_{Π} are coefficients of resistance to the movement of the skidder and the dragging part of the bundle, respectively.

This formula does not take into account the shift of the centre of gravity of the skidder with the share of the bundle relative to the centre of gravity of the skidder itself, which leads to a redistribution of the propulsion pressure on the ground.

Throughout logging trail φ_{T}, φ_{Π} and α may differ and quite significantly.

The above equation only partially reflects the soil conditions by the values φ_{T} and φ_{Π}, and the terrain at an angle α on separate sites. Values of φ_{T} largely depend on the pressure of the movement on the ground, on the state of the surface of movement and other factors. Values of φ_{Π} depend on the composition of the forest stand, the development of the tree crown (when skidding trees), the direction of the tree cords and other factors.

When idling the skidder in this equation $G_{\text{B}} = 0$ and $F_{\text{KX}} = G_{\text{T}}(\varphi_{\text{T}} \cos \alpha \pm \sin \alpha)$, therefore, with cargo and idling speeds, the following can be achieved:

$$V_{\Gamma\text{X}} = \frac{N \cdot \eta}{F_{\text{K}}} \quad (4)$$

and

$$V_{\text{XX}} = \frac{N \cdot \eta}{F_{\text{KX}}} \quad (5)$$

Though, since $F_{\text{KX}} < F_{\text{K}}$, then $V_{\text{XX}} > V_{\Gamma\text{X}}$ and while knowing the length of certain sites, it is not difficult to calculate the time of their passage in the cargo and idle directions.

It can be concluded that, while maintaining the power close to the nominal, one can increase the speed of movement or the weight of a bundle by reducing the weight of the skidder and the coefficient of resistance to movement.

The weight of the skidded bundle can be expressed as:

$$G_{\text{B}} = \frac{N \cdot \eta - G_{''} \cdot V_{\Gamma\text{X}}(\varphi_T \cos\alpha \pm \sin\alpha)}{V_{\Gamma\text{X}}\,[k'(\varphi_{''} \cos\alpha \pm \sin\alpha) + (1-k')(\varphi_{\Pi} \cos\alpha \pm \sin\alpha)]} \quad (6)$$

The maximum allowable value of (G_{B}) weight of the skidded bundle can be calculated for all the sites, by using this formula and the speed of movement, which is the limiting value of the weight of the bundle by this route, and the cycle time for skidding the bundle.

A particular concern is the usage of a certain site. How long can it be used? How many double passes of the skidder and skidder system can be allowed at a particular site to prevent the transition of weak (beneficial) soil damage to strong (harmful)?

The loading point has more double passes when it is closer to the site.

Theoretical studies show that to reduce the cost of developing the cutting area, as well as the degree of damage to the soil, it is necessary to know its detailed characteristics (Dmitrieva et al., 2019; Rudov et al., 2019b, 2019c). Before the development of the cutting area, there must be at least three of its characteristic maps. One should show all the selections, i.e. some parts of the whole cutting area with a certain composition of the tree stand, the average volume of the full-length log and one or another forest reserve per hectare. Other must show areas with approximately the same bearing capacity of soils, including those impassable for the car. On the third—all terrain features—ascents, descents and their parameters, streams, ditches, etc.

If the scales of all the maps are the same, then putting them one on top of another, a rather detailed description of each point of the cutting area will be achieved. By choosing an arbitrary coordinate system, for example, the abscissa axis parallel to the front of the loading, logging trail, or otherwise, one can tie each point to the location and know its detailed characteristics (Grigoriev and Zhukova, 2004).

Division with some forest reserves q_{i} per hectare may have an arbitrary shape square S_{i}. Regardless of the division form, it is always possible to find a forest reserve centre (hereinafter – FRC) on it, by analogy with the centre of gravity of a flat figure of the same density. On the first map, it is possible to determine the coordinates of the FRC (x_{i}; y_{i}), as shown in Figure 1, in which the difficult areas are marked by colour. If the area of the division is too large or the form of the area is too complex, it should be arbitrarily divided into parts. The size of such part, for example, might correspond to the size of the area for one bundle. Also, to determine the FRC of each part and the coordinates on the map (Shapiro et al., 2008; Grigoriev et al., 2011). Then the coordinates of the FRC of the entire division can be calculated by the formulas:

$$x_{\text{i}} = \frac{q_{\text{i}}(S_1 x_1 + S_2 x_2 + \ldots + S_{\text{n}} x_{\text{n}})}{q_1 + q_2 + \ldots + q_{\text{n}}} \quad (7)$$

$$y_{\text{i}} = \frac{q_{\text{i}}(S_1 y_1 + S_2 y_2 + \ldots + S_{\text{n}} y_{\text{n}})}{q_1 + q_2 + \ldots + q_{\text{n}}} \quad (8)$$

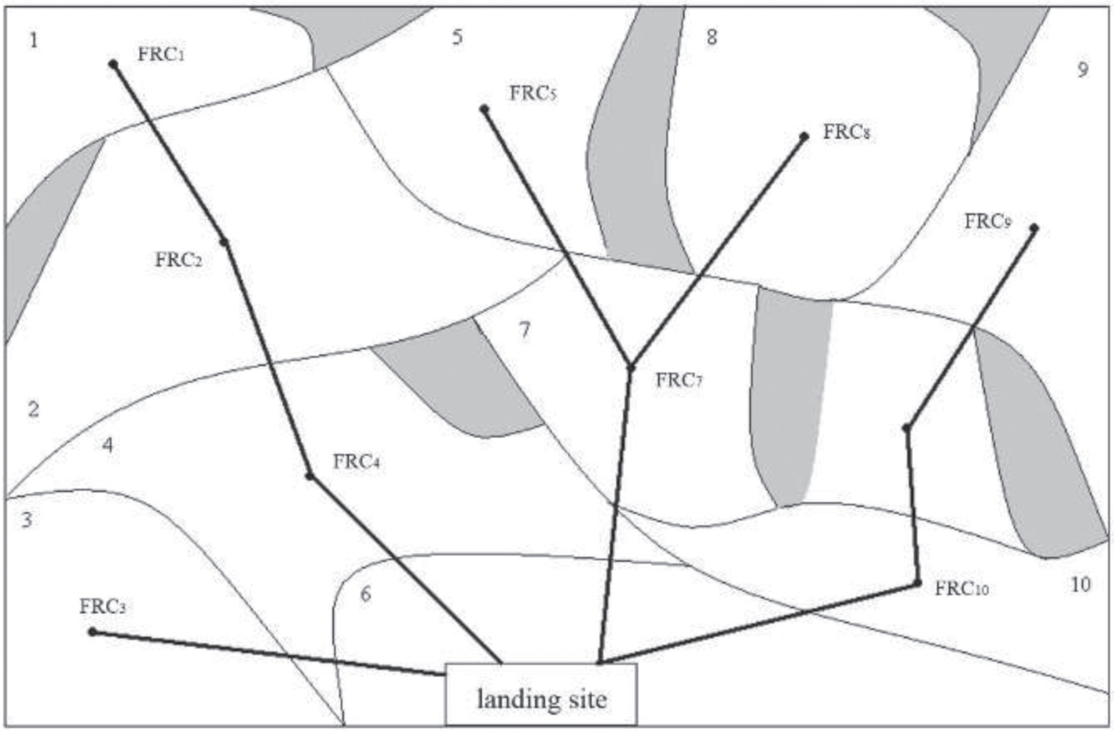

Figure 1: Dividing the cutting area into elementary areas.

where *n* is the number of parts of the divided area and S_n, (x_n, y_n) – area and coordinates of the *i* division.

In general, for several divisions it can be written as:

$$x_{Ц} = \frac{\sum_{i=1}^{Z} q_i S_i x_i}{\sum_{i=1}^{Z} q_i} \quad (9)$$

$$y_{Ц} = \frac{\sum_{i=1}^{Z} q_i S_i y_i}{\sum_{i=1}^{Z} q_i} \quad (10)$$

In those cases, for one reason or another, logging trail is impossible or extremely inexpedient in the FRC of two divisions. Moreover, it is needed to lay it between two adjacent divisions. Then, the coordinates of the point of a conditionally doubled division (consisting of two different in area and forest reserve) can be calculated as (Vysotin and Grigoriev, 2000):

$$x_C = \frac{q_1 S_1 x_1 + q_2 S_2 x_2}{q_1 S_1 + q_2 S_2} \quad (11)$$

$$y_C = \frac{q_1 S_1 y_1 + q_2 S_2 y_2}{q_1 S_1 + q_2 S_2} \quad (12)$$

The route of logging trail from one FRC to a conditionally doubled FRC of two divisions appears to be conjugated. However, straightening of logging trail may be impossible by terrain and soil conditions.

Thus, the coordinate-volumetric method in combination with the terrain and soil restrictions will allow quite reasonably drawing up the layout of the logging trails in the cutting area. Thereby, reducing to the minimum possible energy and material costs for logging trees, as well as reducing to the minimum the deterioration of forest conditions due to reduce in the total compressing effect of logging systems on the soil of the cutting area.

Such a technique can be applied in the construction of the forest logging trails. Only instead of the term “division”, it should be the term - cutting area. The scales of the maps and the location of the coordinate axes may be different; in particular, they may coincide with the geographic coordinate system.

Logging trailswear strongly influences the coefficients φ_T and $\varphi_П$ of resistance to skidder movement and the dragging of a bundle of full-length log or trees, although this relationship is not always clearly visible. The formation of a wheel gauge depends on soil conditions. In some cases, in process of work, that is, when the number of double passes of the skidder in some places increases, the soil under the tracks or wheels is first indurated and compacted and φ_T decreases. Then indurated layer collapses, the depth of wheel tracks and φ_T increases. In other cases, the soil under the tracks or wheels is indurated very weakly and almost immediately begins to collapse, the depth of the wheel track is constantly increasing and φ_T quickly reaches the limit values (Grigoriev and Rudov, 2018; Manukovsky et al., 2018; Mokhirev et al., 2018; Rudov et al., 2018, 2019d).

To assess the degree of broadening of a logger trail in certain sections, one must know the required double skidder moves on it. The length of logger trail L is such that it intersects n adjacent divisions with areas S_i and forest reserves per hectare q_i. The total amount of wood V_B that is necessary to skid along this route to the loading point and the total number of double moves Z_{max} of the skidder can be calculated if the volume V_Π of the skidded bundle is determined taking into account the terrain-soil constraints.

$$V_B = \sum_{i=1}^{n} S_i q_i \quad (13)$$

$$Z_{max} = \frac{V_B}{V_\Pi} \quad (14)$$

The length l_1 of this part of the logger trail can be taken equal to the distance from the loading point to the FRC of the closest division, which is calculated according to the coordinates of the FRC and the loading point, as the distance between two points by the formula:

$$l_1 = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (15)$$

or on a map with a specific scale using a ruler.

The volume of the full-length log, skidded on the second division of the logger trail from the FRC of the first division to the FRC of the next division, is smaller by the amount of volume skidded from the first division.

$$V_{B1} = V_B - S_1 q_1 \quad (16)$$

and the amount of double moves:

$$Z_{max-1} = \frac{V_B - S_1 q_1}{V_\Pi} \quad (17)$$

The length of the second logger trail can be determined similarly to the first.

The following volume of the full-length log must be skidded at the most remote part of the logger trail:

$$V_{Bn} = S_n q_n \quad (18)$$

and make the number of double skidder moves:

$$Z_{min} = \frac{S_n q_n}{V_\Pi} \quad (19)$$

The planned operating time for a particular section of the route, combined with knowledge of the bearing capacity of the soil and the topography of each section, will approximately reduce the energy consumption for tree skidding and soil damage. However, it is necessary to take into account that any overload of the skidder, to reduce the number of transportations, in excess of permissible ones either lead to its breakage, or significantly reduce its durability (Dobretsov and Grigoriev, 2018).

Thus, a detailed description of the soil and terrain conditions of the cutting area in combination with the coordinate-volumetric tracing method allow obtaining the following layout of the paths for skidding. Such layout can reduce the total costs of skidding to the most advantageous, and reduce a damage to the soil to the required natural reforestation level, and ultimately improve the environmental performance of skidders (Grigorev et al., 2018).

Figures 2 and 3 show the layout of logging trails, respectively, calculated by the proposed method and with a standard parallel layout (Patyakin et al., 2012). Figure 1 maps the cutting plots, with grey areas highlighting the difficult-to-reach and non-operating areas, which allows logging trails to be positioned in such a way that they do not intersect those areas. Accordingly, this reduces the energy intensity of the process of logging trail. When using the standard layout of logging trails (Figure 3), logging trails often cross difficult-to-reach areas, which leads to an increase in the cost of the skidding itself, as well as preparatory and auxiliary work.

Result and Discussion

The approach is widely used when the cutting area is divided into non-intersecting areas of a set of wood bundles. Each area is assigned a generalized coefficient. Such coefficient characterizes the degree of impact of the skidder on the soil of the area according to the following rule. The larger the coefficient, the weaker the soil and, therefore, negative impact of a skidder is stronger. This approach can be continued by dynamic programming with the criterion of minimizing the total impact of skidding on the soil.

The disadvantages of this approach are the restrictions on the form of the cutting area, the form and size of the territory of a set of wood bundles, binding to a specific loading point. Such a model does not fully take into

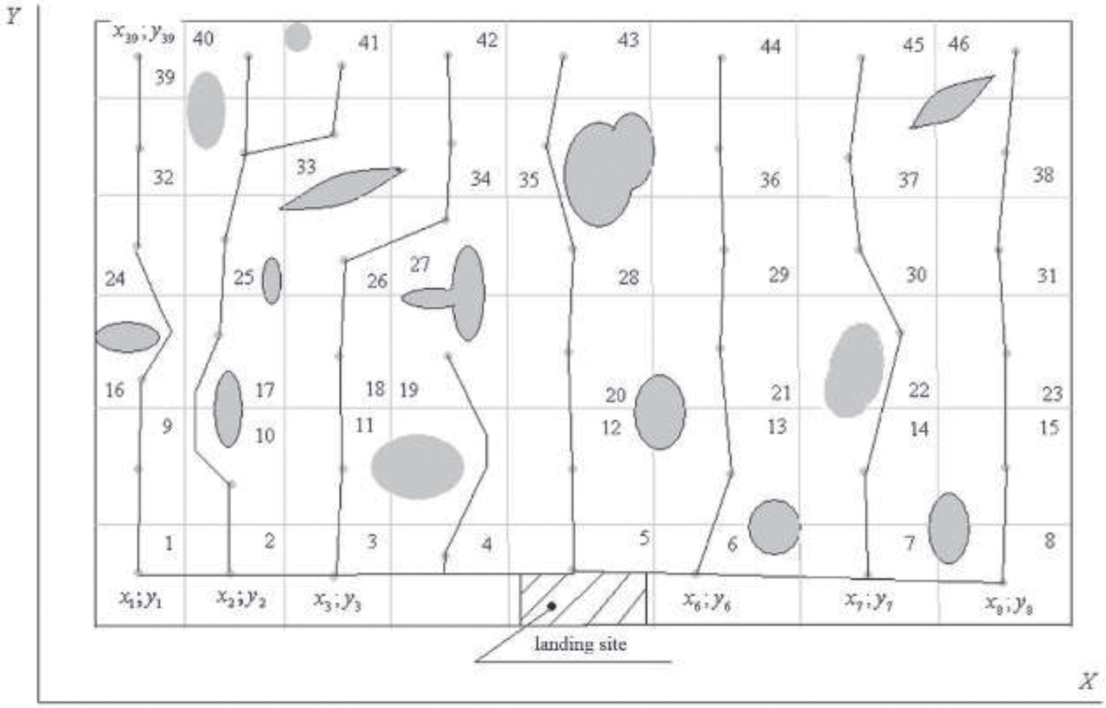

Figure 2: The layout of the logging trails according to the proposed method of calculation (difficult-to-reach and non-operating areas are highlighted in colour).

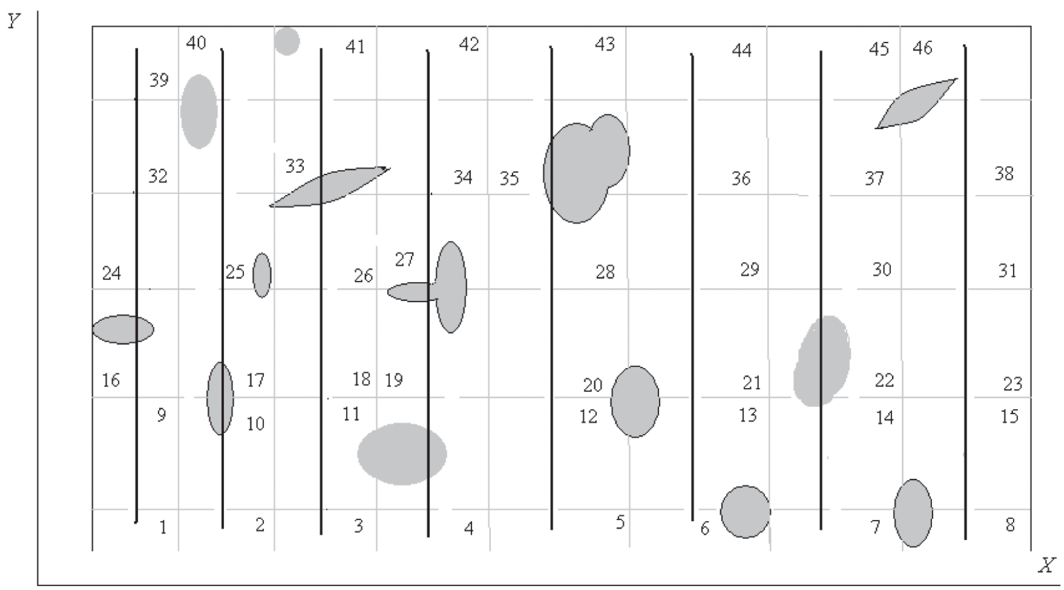

Figure 3: Parallel logging trails layout.

account the uneven growth of the forest, the terrain of the cutting area, and the manoeuverability of the logging equipment. In addition, the site for collecting bundles of wood has a large size and it is difficult to characterize it unambiguously with a single value, which shows the properties of the soil (Voronova and Piskunov, 2011).

To eliminate these drawbacks, it is proposed to use hypernetwork models.

The construction of trails of forest machines in the form of two related subtasks is considered. The first involves division of the entire territory into non-intersecting areas of a set of wood bundles. In the second, the selected areas are linked into a single transport network, which determines the direction and procedure for bypassing the areas of the cutting area during skidding (Voronova et al., 2012).

The traditional approach involves solving two subtasks separately. In the classical formulation, these subtasks are formulated as follows.

Task on coverage of a finite set V by subsets W of set V, by those which $\bigcup_{w \in W} w = V$, and a given weight function on subsets h: $W \rightarrow R^+$, is to search for a subset $S \subset W$, where the weight function $\sum_{w \in S} h(w)$ takes the minimum value.

The task of finding the minimum spanning tree graph $G = (W, E)$, with a given weight function on arcs h: $E \rightarrow R^+$, is to search for a subgraph of graph G, which is a tree, contains all the vertices of the graph G and has a minimum weight.

The solution of the original problem implies a coordinated solution of the above subtasks, since the parameters of the designed transport network depend both on the found division of the territory into regions, and on the order and direction of their bypassing. Modelling of the transport network of the cutting area in the form of a two-tier hypernetwork allows linking two subtasks; also, formulating one task of covering the hypernetwork with a root tree (Voronova et al., 2012b).

The use of hypergraphs and hypernetworks for the design of transport networks in the cutting area allows simultaneously to take into account the parameters of the transport network, which are not taken into account in the above works—such as the topography and soil of the cutting area, the relative position of the main transport routes. In addition, the direction of movement through the transport networks, the load on the territory, coverage of the entire territory (Voronova et al., 2013).

When carrying out logging, the harvested wood is delivered to the forest log depot along temporary transport routes, called logging trails, which form a transport network covering the entire territory of the cutting area. The transport network must be designed taking into account the features of the terrain, the properties of the soil and the parameters of the logging equipment (Khakhina et al., 2018).

When designing a transport network, it is necessary to minimize the impact of skidding equipment on soils, direct the main traffic flows through areas with strong soils capable of withstanding heavy loads, and relieve areas with weak soils.

There are standard schemes of transport routes that have a regular structure: with parallel, diagonal, radial, fan placement of logging trails (Grigoriev et al., 2012; Patyakin et al., 2012). However, such schemes poorly take into account the peculiarities of the terrain and the soil properties of specific cutting areas. The use of standard location schemes of logging trails often leads to significant soil damage and destroys the forest ecosystem.

Area D is a projection of the cutting area on the plane xOy. Area D is divided by the regular grid with spacing l (m), formed by two families of lines: parallel to the axis Oy and parallel to the axis Ox.

The top of the hypernetwork is compared to each cell of the grid model of the cutting area. The subsets of vertices form hyperedges of hypernetworks. Vertices and hyperedges make up the lower level of the hypernetwork. At the top level of the hypernetwork, nodes correspond to hyperedges, arcs unite hypernetwork nodes into a single network.

Hypernetwork is $A = (V, W, E, F', F'', G)$, in which: V is set of vertices, W – set of hyperedges, E – set of arcs, F': $W \rightarrow 2^V$, F'': $W \rightarrow 2^V$ – mappings, assigning to each hyperedge $w \in W$ two subsets $F'(w) \subset V$ and $F''(w) \subset V$ of its vertices, mappings F' and F'' are not injective, F' defines a set of vertices, corresponding to the sections of the direct passage of the skidder and F'' is set of vertices, relevant to areas that fall within the reach of the skidder.

G: $E \rightarrow W \times W$ is injective mapping that matches each arc $e \in E$ with ordered pair $G(e) = (w_1, w_2)$ of hyperedges of set W, w_1 and w_2 are designations for the first and second elements of the pair $G(e)$.

Thus, these three $A'_1 = (V, W, F')$ and $A''_1 = (V, W, F'')$ are hypergraphs, and other three $A_2 = (W, E, G)$ – digraph. In digraph A_2 hyperedges of set W will be called nodes.

Let $T = (S, r, p)$ be root tree in digraph A_2, in which: $S \subset W$ is set of tree nodes, $r \in S$ – root of tree and p: $S \rightarrow S$ – mapping, matching each node $s \in S$ with its parent $p(s)$ in tree. It means that if tree T has an arc (w_1, w_2), then $p(w_1) = w_2$ (all arcs of the root tree are directed to the root).

Mapping p must have the following features: (1) $p(r) = r$ and (2) for any $s \in S$ $\underbrace{p(...p(p(s))...)}_{|S|} = r$

The second property means that from any node of the tree there is a path to the root consisting of the arcs of the tree.

The tree $T = (S, r, p)$ covers the top $v \in V$, if there is $s \in S$, for which $v \in F''(s)$.

The root tree is called T spanning tree of hypernetwork A, if the union of the lower level hyper-edges of the hypernetwork, corresponding to the nodes of the tree, is equal to the set of vertices: $\bigcup_{s \in S} F^{//}(s) = V$

Thus, the covering tree of the hypernetwork covers all its vertices. A top-level arc is incident to a lower-level hyperedge, if this hyperedge corresponds to a top-level node that is incident to this arc. The arc of the upper level covers the top of the lower level if the vertice belongs to the hyperedge incident to this arc.

J is mapped as index set of soil consistencies, $J = \{1,\ldots,m\}$. As the index increases, the soil consistency type will deteriorate.

I is mapped as index set of categories of gauge depth, $I = \{1,\ldots,n\}$. As the index increases, the depth gauge category will deteriorate.

For each vertice $v \in V$ of hypernetwork, there are the following features: $k(v) \in J$ soil consistency, $h(v)$ height above sea level (m), $z(v)$ forest reserve (m^3).

For each hyperedge $w \in W$ it is necessary to define $K(w) \in J$ soil consistency as the worst soil consistency value across all vertices $F'(w)$:

$$K(w) = \min_{v \in F'(w)} k(v), \forall w \in W \tag{20}$$

For each hyperedge $w \in W$ the initial vertice is denoted $beg(w) \in F'(w)$ and the end vertice $end(w) \in F'(w)$. Pair of vertices $track(w) = (beg(w), end(w))$ is a directed segment, determining the trajectory and direction of movement of the skidder when picking a bundle from the territory corresponding to the hyperedge. $\varphi^{track(w_1)}_{track(w_2)}$ depicts the angle between the segments of the corresponding adjacent hyperedges of hypernetwork A:

$$\varphi^{track(w_1)}_{track(w_2)} : \exists\ e \in E \mid G(e) = (w_1,\ w_2) \tag{21}$$

$$0^0 \le \varphi^{track(w_1)}_{track(w_2)} \le 180^0 \tag{22}$$

$\mu(w) = |F'(w)|$ is power set $F'(w)$, $w \in W$. $Q = v_1, v_2, \ldots, v_{\mu(w)}, \in F'(w)$ is sequence of vertices along a directed segment $track(w)$ from set $F'(w)$ for hyperedge $w \in W$.

For each hyperedge $w \in W$ it is necessary to determine the height differences between adjacent vertices of the sequence Q:

$$\Delta H_{q-1}(w) = h(v_q) - h(v_{q-1}) \tag{23}$$

$$\forall q = 2,..,\mu(w), \forall w \in W \tag{24}$$

$t = |S|$ is power of set S. Root tree T might be called *marked*, if all the nodes are numbered from 1 to t in order of bypassing by the skidder of the territory, corresponding to the nodes, when collecting wood. Then for each node $s \in S$ it might be denoted by $\pi(s)$ set of nodes of tree T, whose numbers are less than the node number s, i.e. the corresponding territory is bypassed by a skidder earlier.

For each node $s \in S$ of tree T it might be necessary to define the residual set:

$$U(s) = F''(s) \setminus \left(\bigcup_{w \in \pi(s)} F''(w) \right), \forall s \in S \tag{25}$$

For each node $s \in S$ of tree T it might be necessary to define the residual forest reserve:

$$Z(s) = \sum_{v \in U(s)} z(v), \forall s \in S \tag{26}$$

$N(s)$ is depicted as the number of descendants of the node $s \in S$ in tree T, including the node itself s. $N(s)$ determines the number of passages through the skidding area corresponding to the node $s \in S$.

For assortment technology of timber logging, calculation $N(s)$ is made taking into account the types of wood.

C is depicted as index set of assortments $C = \{1, \ldots, u\}$.

$\theta(c, v)$ is share of type c for vertice v, $c \in C$, $v \in V$.

Then $\Theta(c, s)$ is share of type c for node s, $c \in C$, $s \in S$.

$$\Theta(c,\ s) = \frac{\sum_{v \in U(s)} \theta(c,\ v)}{|\pi(s)|} \tag{27}$$

$O(s)$ is set of descendants of the node s in tree T, $s \in S$.

$$N(s) = \sum_{c \in C} \left\lceil \sum_{s \in O(s)} \Theta(c,\ s) \right\rceil \tag{28}$$

Given function $\Phi : J \times Z^+ \to \mathrm{I}$, which for fixed $j \in J \Phi(j,\ g)$ as function from $g \in Z^+$ is a non-negative increasing concave function. Function Φ determines the dependence of the formation of the gauge category for each soil consistency depending on the number of drives of the skidder.

As an optimality criterion, the lexicographic objective function can be defined $(y_1,\ldots,y_n) \to \min$ which minimizes the number of tree nodes corresponding to the territory where the logging trails are located, in ascending order of the gauge category index. Vector component y_i is number of nodes set S of tree T, corresponding to the logging trails with an index of the depth gauge category i, $i \in \{1,\ldots, n\}$:

$$y_i = \#\{s \mid s \in S, i = \Phi(K(s), N(s))\}. \tag{29}$$

Vector $(y_1,\ldots,y_n)$ might be called estimated function of the spanning tree, and the components of the vector are parameters of the estimated function.

An optimization problem might be formulated. For a given hypernetwork A and numbers P, α, l, γ_{up} and γ_{down} it is required to find the root tagged covering tree $T = (S, r, p)$, for which, vector $(y_1,\ldots,y_n)$ takes a minimal value and:

1. For each node $s \in S$ of tree T residual stock $Z(s) \le P$, $\forall\ s \in S$, where P is permissible volume of a bundle of wood (m^3) for skidder.
2. For each pair of adjacent tree nodes T the angle between the directed segments of adjacent nodes and s_1 and s_2 is limited α where α is unacceptable angle of rotation of skidder:

$$\varphi_{track(s_2)}^{track(s_1)} \le \alpha,\ p(s_1) = s_2, s_1,\ s_2 \in S\,.$$

3. For each node $s \in S$ of tree T vertice differences between adjacent areas lie within $[tg(\gamma_{up})\cdot l,\ tg(\gamma_{down})\cdot l]: \gamma_{up} < 0, \gamma_{down} \ge 0, \gamma_{up}$ is maximum tilt angle when moving up the skidder, γ_{down} – maximum tilt angle when moving down the skidder and l is step (m) of an overlaying net:

$$tg(\gamma_{up}) \le \frac{\Delta H_{q-1}(s)}{l} \le tg(\gamma_{down}) \tag{30}$$

$$\forall q = 2..\mu(s), \forall s \in S \tag{31}$$

In the presented model, small non-intersecting fragments of the sites correspond to the vertices. Forest harvesting areas correspond to the hyperedges. The skidder moves along such areas, where it fully loads and moves wood to the forest log depot. Possible logging trail sites correspond to the directed hyperedges.

Here is a generalized rooted-tree algorithm for calculating the hypernetwork coverage with a known nesting depth d.

The algorithm for solving the considered problem is based on a search with a return. Initially, the root tree consists of a single node. Then, at each iteration, an arc is sought, the addition of which to the tree will lead to the smallest increase in the value of the objective function. The search for such an arc is carried out by searching all possible options for adding no more than d arcs to the tree. Parameter d is selected depending on the number of nodes of the second level digraph.

The pseudo code of the proposed algorithm for constructing the covering tree of the hypernetwork T with root r.

$$FindTree(T, r, d) \tag{32}$$

$$T = tree(r) \tag{33}$$

while not cov(T, V) do

$$e' = \arg\min \left\{ g\begin{pmatrix} add\,(T,e), 1, f\,(T), \\ area\,(T),\ d \end{pmatrix} \mid e \in set\,(E,T) \right\} \tag{34}$$

$$T = add\,(T, e') \tag{35}$$

return T

At the beginning of the algorithm FindTreetree T consists of one root r. Then, at each iteration of the "while" cycle, all possible options of trajectory for adding to the tree of no more than d arcs. The best trajectory is that, for which the ratio of the increment of the objective function of the problem to the increment of the number of covered vertices will be minimal. As a result, the first arc of the best trajectory is added to the tree. This process is repeated until the tree covers all the vertices of the hypernet.

The set of first arcs of trajectories is generated using the function *set*(E, T). Function *add*(T, e) forms a new tree with an added arc e. Function *area*(T) returns many tree-covered vertices T. Function g(...) enumerates the trajectories of adding arcs.

The auxiliary functions of the algorithm are described in more detail.

Recursive function $g(T, M, f_0, Q, d)$ designed to iterate the trajectories of adding no more than d arcs, returns the ratio of the increment of the objective function of the problem to the increment of the number of covered vertices. $T = (S, r, p)$.

Step 1. If ($M > d$ or set $(E, T) = \varnothing$) and

$$\left(\left| \bigcup_{s\in S} F''(s) \setminus Q \right| = 0 \right), \tag{36}$$

then return ∞.

Step 2. If ($M > d$ or set $(E, T) = \varnothing$) and

$$\left(\left| \bigcup_{s\in S} F''(s) \setminus Q \right| \ne 0 \right), \tag{37}$$

then return

$$\frac{f(T) - f_0}{\left| \bigcup_{s\in S} F''(s) \setminus Q \right|} \tag{38}$$

Step 3. If ($M \le d$ and set $(E, T) \ne \varnothing$) , then return

$$\min\{g\,(add(T,e), M+1, f_0, Q, d) \mid e \in set(E,T)\} \quad (39)$$

Function $f(T)$ designed to calculate the objective function σ for tree $T = (S, r, p)$: $\sigma = \sum_{s \in S} \Omega(s, N(s))$, where σ is general view of the objective function that summarizes the node weights $s \in S$ of tree, the weight of the node depends on the number of descendants of the node $N(s)$ in tree.

Function *tree*(r) of building the initial tree T, consisting of one tree r: $S = \{r\}$, $p(r) = r$,

$$T = (S, r, p). \quad (40)$$

Function cov(T, V) is intended to check if vertices are processed, returns the verity if all vertices are processed *area*(T) = V, otherwise false.

Function *set*(E, T) is designed to define a set of arcs E', the beginning of which does not belong to the tree T, and the end belongs to the tree $T = (S, r, p)$:

$$E' = \{e \in E \mid e = (w_1, w_2),\ w_1 \notin S,\ w_2 \in S\} \quad (41)$$

Function *add*(T, e) is designed to form a new tree T' by adding to the tree T arc $e = (w_1, w_2)$, returns the tree $T' = (S', r', p')$, where $p' = p$, $p'(w_1) = w_2$, $S' = S \cup w_1$, $r' = r$.

Function *area*(T) is designed to build a set of vertices Q, covered by tree $T = (S, r, p)$:

$$Q = \bigcup_{s \in S} F''(s). \quad (42)$$

A special case of the algorithm for constructing the spanning tree, taking into account the additional constraints of the problem under consideration is considered. Nesting depth parameter $d = 1$.

The algorithm is described for constructing the root covering tree of the hypernetwork of minimum weight for solving the considered problem for a given root r.

Step 1. Mark all vertices V as uncovered. Covering tree T is empty.

Step 2. Add root r in covering tree T.

Step 3. Since there are uncovered vertices V and set of hyperedges W is empty, step 4 might be made, otherwise step 10.

Step 4. Assign a record *Record* = ($Y_{\text{rec1}}, \dots, Y_{\text{rec n}}$) with great value.

Step 5. While the set of the hyperedges is not empty, then to implement step 6, otherwise step 9.

Step 6. Choose trial hyperedge $w_{\text{test}} \in W$. Calculate the residual hyperedge margin $Z(w_{\text{test}})$, junction angle of a directed segment of hyperedge $\varphi_{track(s_1)}^{track(w_{test})}$, $p(w_{\text{test}}) = s_1$, $s_1 \in S$, height differences of hyperedge $\Delta H_{q-1}(w_{test}), \forall q = 2..\mu(w_{test})$. If restrictions are fulfilled (1–3) of model, then step 7, otherwise step 5.

Step 7. Calculate consistency of hyperedge $K(w_{\text{test}})$. Experimentally add the node corresponding to the hyperedge and the arc to the covering tree. Experimentally count the number of descendants $N(s_{\text{test}})$ for all ancestors of the node $s_{\text{test}} \in O\ (w_{\text{test}})$. Calculate the estimated covering tree function ($y_1, \dots, y_n$. If the evaluation function is less than the record, then step 8, otherwise step 5.

Step 8. Assign to the record the current value of the evaluation function Re*cord* = ($y_1, \dots, y_n$), remember the current hyperedge as a record $w_{\text{Rec}} = w_{\text{test}}$. Go to step 5.

Step 9. Add a record hyperedge to a covering tree $S = \{w_{\text{Rec}}\} \cup S$. Recalculate the number of descendants $N(s)\ \forall\ s \in S$ for tree nodes, estimated tree function ($y_1, \dots, y_n$). Update set of hyperedges W not participating in the coverage, update the set of covered vertices V of hypernet. Move to step 3.

Step 10. Exit.

The result of the algorithm is illustrated using an example (Figure 4). The calculation is made on the hypernetwork with 562 vertices, 409 hyperedges (nodes), more than 2000 arcs. For example, field data is used from one of the logging enterprises of the Republic of Karelia. Nodes consistency $K(s)$ is shown in shades of gray: the thicker the colour is, the higher the soil consistency index J. The thickness of the lines of the covering tree determines the gauge depth indicator: the thicker the line, the higher the gauge depth index I. The black square is the root of the covering tree.

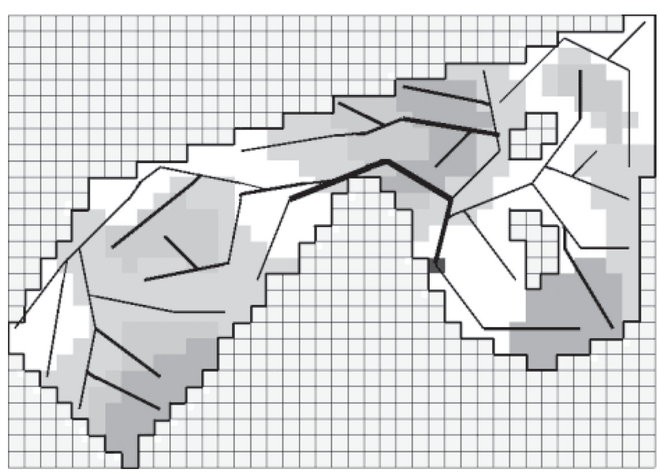

Figure 4: An example of constructing the covering tree of the hypernetwork.

Small modifications of the algorithm make it possible to obtain covering trees with a more regular structure: with parallel, diagonal or fan placement of directional segments of covering nodes. Thus, the introduction of restrictions on the number of turns (exceeding a certain angle), when adjoining the directed segments of hyperedges, allows adjusting the nesting of the directed segments of the covering tree. Constraints were set on the junction of the directed segments of the hyperedge at approximately equal angles to the directed segment of the parent hyperedge. Such constraints allow obtaining a covering tree scheme with parallel placement of the directed segments of the covering nodes. Figure 5 shows examples of covering trees with a regular structure.

In order to find the root r of a covering tree, it is needed to fulfill the steps of the algorithm for constructing the root covering tree of the hypernetwork of minimum weight for different variants of root placement and choose the one that corresponds to the smallest value of the objective function.

An analysis of the algorithm is given. The FindTree algorithm is heuristic and, in general, may not provide optimal solutions.

If the end of any arc $e \in E$ is equal to a root ($w_2(e) = r$), then the considered problem turns into the task of constructing the minimum weighted coverage of the set V of subsets of vertices $F''(w) \subset V$. Every subset $F''(w)$, $w \in W$ has its weight $\Omega(w, 1)$. In this case, algorithm FindTree while $d = 1$ gives solution, worse than optimal no more than in $\ln(|V|) + 1$ times.

If for any hyperedge $w \in W$, function $\Omega(w, N(w))$ is linear and all subsets $F''(w)$ do not intersect in pairs, then the considered algorithm with $d = 1$ coincides with Dijkstra's algorithm for finding the shortest paths and gives an exact solution to the problem.

If for any hyperedge $w \in W$, function $\Omega(w, N(w))$ is constant, all subsets $F''(w)$ pairly do not intersect, and for every arc $e \in E$ there are reverse arc, the specified algorithm when $d = 1$ coincides with the Prim's algorithm for constructing a minimal covering tree of an undirected graph and also gives an exact solution.

The time complexity of FindTree algorithm in the worst case is equal to $O(|V|^{2d+1})$, since at each step it moves no more than $|V|$ adding trajectories no more than d arcs and adding each arc should cover at least one new vertice. While $d = 1$, the complexity of the algorithm is achieved $O(|V|^3)$.

To reduce the operation time of the algorithm, it is proposed to use the "binary heap" data structure for storage for each possible upper-level arc of the hypernet from the set E. Hence, for each possible arc to add. The increment of the objective function.

Binary heap is an array with certain orderliness properties. An array *Mas* will be considered as a binary tree. Each vertice of the tree corresponds to an element of the array. If the vertice has an index v then her parent has an index $[v/2]$ (the vertex with index 1 is the root), and its children are indexes $2v$ and $2v + 1$. Elements, stored in the heap have the main property of the heap: $Mas[Parent(v)] \leq Mas[v]$. It follows that the value of the ancestor does not exceed the value of the descendants. Therefore, the smallest element of the tree is at the root of the tree. The height of the tree is $O(\log n)$, where n is number of heap items. The time of the main operations on the tree is proportional to its height and is $O(\log n)$.

In this case, in the first step of constructing the scheme of the logging trails, it is necessary to build a "binary heap" consisting of $|E|$ elements according to the number of possible arcs, the value of the heap elements contains an increment of the objective function that will cause arcs to be added to the covering tree. The time complexity of the heap build operation is $O(|E|)$.

Further, at each step of the algorithm, an element will be selected with a minimum increment of the objective function, which is located in the root of the binary tree. In addition, add the corresponding arc to the top-level graph that defines the scheme of logging trails. In this case, it will be needed to recalculate the values of those

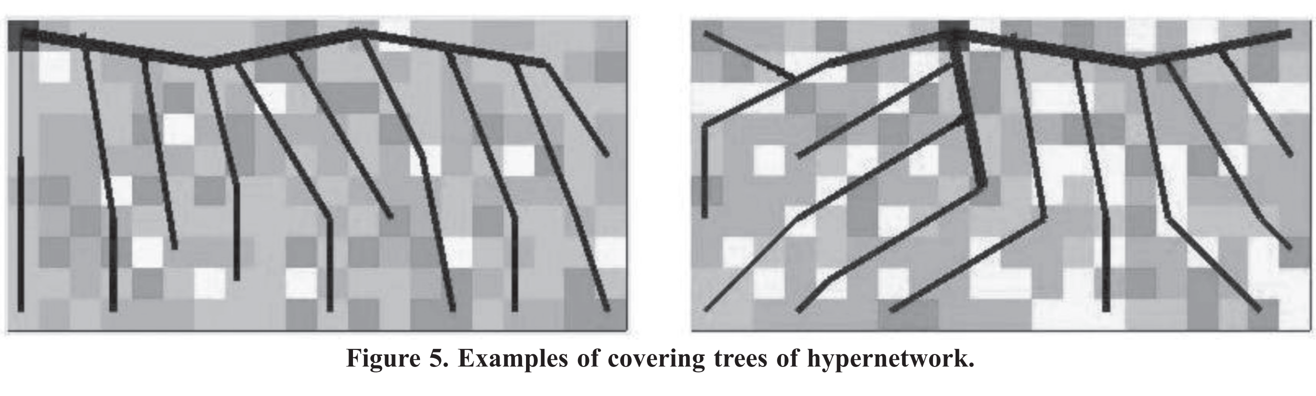

Figure 5. Examples of covering trees of hypernetwork.

elements of the binary heap that correspond to the arcs incident to the newly selected arc. The constant C is maximal demidegree of hyperedge outcome $\forall\ w \in W$. Then while recalculating C elements of a binary heap, it is required to perform C operations to restore the main property of the heap. In addition, when removing the root element from the heap, the rightmost leaf of the tree is assigned a new root element and pushing it down the tree as far as possible. The time complexity of the recovery procedure for the main heap property is $O(\log|E|)$.

In the worst case, each addition of an arc to the top-level graph of a hypernetwork only one vertice is covered V of lower level of hypernet. Then for covering all the vertices V the procedure of increasing arcs in the top level graph will have to be performed at worst $|V|$ times.

Thus, the operational time of the algorithm is $O(|E| + |V| \cdot C \cdot \log(|E|))$. It might be noted that $|E| < C\ |V|$. Thus, the operational time of the algorithm for constructing a scheme of logging trails using a binary heap while $d = 1$ equals $O(|V| \cdot C \cdot \log(|E|))$, which is less than $O(|V|^3)$.

Using a binary heap to store data (e.g., the objective function increments) simplifies the algorithm.

The necessary conditions are described for the existence of the covering tree of the hypernetwork. For any vertice of the lower level $v \in V$ of the hypernetwork, there must be a top-level hyperedge containing this vertice (a hypernetwork node) $w \in W$, for which there is a path to the root r, consisting of upper level arcs E of digraph A_2.

The procedure is described for verifying the condition of the existence of a solution. This procedure is a modification of the algorithm for traversing the graph in width, as applied to hypernets. The search for raw vertices goes wide, first, all adjacent nodes (neighbours) for the selected node are opted r, and then neighbours of neighbours. To memorize nodes that have not yet been processed, a queue is used, and to memorize nodes that have already been processed, an auxiliary list.

First, all vertices are marked $v \in V$ as unprocessed. The auxiliary list is empty. Next, the starting node is set r. The starting node is included in the queue. Until the queue is empty, the following steps are performed:

- Removing from the queue the next node $w_{add} \in W$. Checking the processing of this node by the auxiliary list. If the node has already been processed, the next node from the queue will be extracted. If the node has not yet been processed, then it will be processed and put in the list of processed nodes.
- Marking all vertices as processed $v \in F''(w_{add})$, which belong to the processed node (hyperedge) w_{add}.
- Queueing all unprocessed nodes $w_1(e) \in W$, which are the beginning of arcs $e \in E$, the end of which is the current node $w_2(e) = w_{add}$.

If, after performing the checking procedure for the solution existence, all vertices $v \in V$ will be processed, then a covering tree can be built T of hypernetwork, otherwise the construction of the covering tree is impossible.

For carrying out simulation experiments, a vertices $v \in V$ consistency $k(v)$ input parameter generator was developed for the hypernetwork coverage algorithm, which is an algorithm for constructing a matrix with a given value of rows and columns and contains pseudo-random simulated values of the variable $k(v)$ with a given distribution law.

The general principle is presented of generating values of a pseudo-random variable. A uniformly distributed discrete random variable is simulated on the segment [1, 10]. The segment is divided[1, 10] into four intervals (according to the number of possible values $k(v)$), the length of which is equal to the frequency of occurrence of soil consistency values. Each interval is assigned with a value of a random variable. Further, depending on the interval in which the simulated value is assigned, this will determine the corresponding value $k(v)$.

For each $k(v)$, 10 experiments are generated, containing a different ratio of solid, solid-plastic, and soft-plastic, flowing soil grounds. Size of simulated cutting area is 100 m × 200 m. When overlaying a grid with a step $l = 10$ m, the territory of 10 × 20 sites is achieved. Realizable stock of wood is 120 cubic metres/hectare, which is distributed evenly in the cutting area. Wood bundle volume $P = 11\ m^3$. On the basis of data on the consistency of the soil and ground areas of the cutting area, issued by the generator, graphs of the lower level of the hypernetwork are constructed. 50 experiments with 200 vertices, approximately 200 hyperedges (a hyperedge unites nine vertices of the hypernetwork), more than 1500 arcs are generated.

The algorithm is implemented in the Microsoft Visual Studio. NET 2008 in programming language C#. Simulation experiments were carried out to analyze the dependence of the following parameters on the nesting depth of the algorithm (the number of arcs d in trial

Table 1: Evaluation of the operation time of the algorithm

Nesting depth, d	*Operation time of the algorithm (c)*	*Vertices covering, (%)*	*Reducing the number of nodes, (%)*
1	0.1	87.4	0
2	1.9	92	4
3	39.9	92.5	5
4	758.1	93.1	5.5

trajectories): the operational time of the algorithm, the percentage of coverage of the vertices of the hypernetwork, the percentage decrease in the number of nodes with an unacceptably deep and critical gauge.

Table 1 shows the average operation time of the algorithm, the percentage of coverage of the vertices of the hypernetwork and the percentage of reducing the number of nodes of the covering tree with an unacceptably deep and critical gauge compared to d = 1 in 50 experiments with different parameter values d = {1, 2, 3, 4}.

Conclusions

The tests and analysis of the hypernetwork covering trees showed the stability of the algorithm for constructing the hypernetwork covering trees. The percentage of covered vertices at d = 1 in average is 87.4%. For 95% of all experiments while d = 1 the coverage percentage of the hypernet vertices is in the range from 80 to 93%.

The table confirms the exponential increase in the time of the algorithm, depending on the nesting depth of the algorithm d. There is a slight increase in the average number of covered vertices when d = 2, with further growth of the parameter d the growth of the average number of covered vertices is insignificant. There is also a slight decrease in the number of nodes of the covering tree with an unacceptably deep and critical gauge when d = 2; with further growth of the parameter d the decrease in the number of nodes is insignificant. Therefore, it is recommended to use the hypernetwork coverage algorithm with d, equal to 1 or 2. A further increase in the nesting depth of the algorithm is impractical.

As a result, an information system has been created that is designed to carry out the integrated design of the forest machine tracks used for logging trail, taking into account the main indicators of the cutting area and the technical characteristics of logging equipment (Voronova and Voronov, 2013).

This software package allows solving the following tasks:

1. Designing the trails of forest machines on the territory of the cutting area, taking into account the consistency of the soil, forest reserves, topography, payload and manoeuverability of equipment.
2. Search for the location of the forest loading point in the cutting area should be implemented taking into account the properties of the soil in the location of the forest loading point. During the search for the location of the forest loading point, it is also necessary to take into account the area adjacent to the forest storage yard. The search is carried out with a choice throughout the cutting area, and the choice of several possible locations indicated by the expert after inspecting the cutting area.
3. The visualization of the received layouts of loading and transport facilities in the cutting area includes the following. The implementation of algorithms for presenting the cutting area in the form of sites. The sites are in different shades of colour, the shades of colour characterize the categories of properties of the soil. There is also the implementation of algorithms of the received layouts of logging trails of different thickness. The thickness of the logging trail characterizes the resulting gauge depth after passage of skidding equipment.
4. Calculation of the main parameters of the received cutting area development scheme: the average length of the skidding paths from the loading point to the unloading point; the total length of the skidding paths. There is also the relationship of certain part of cutting area (occupied by the skidding paths) to the total cutting area. In addition, there is the number of skidding paths categorized by depth gauge: recommended, deep, unacceptably deep and critical.

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