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Economic Comparison of Options for the Transport-Technological Development of the Forest Quarter Network

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Abstract: The article presents an economic comparison of options for the transport and technological development of forest quarters. It examines three principal layouts for main skid trails: diagonal, perpendicular, and curvilinear. The key comparison criterion is the skidding cost, which is directly determined by the average skidding distance. For each layout, detailed calculation models and analytical dependencies are developed to determine the average skidding distance and the skidding work (load-distance), taking into account the dynamics of quarter development and wood increment. A comparative analysis shows that each option has its own area of economic feasibility depending on the quarter's dimensions and the distribution of forest resources. The practical significance of the work lies in providing a tool for the quantitative justification of design decisions, which helps optimize operational costs, increase productivity, and reduce environmental impact on the forest ecosystem.

1 INTRODUCTION

Currently, there are many methods for developing forest fund allotments, but most often, the developed compartments are scattered across different quarters. A disadvantage of such methods is that the placement of final felling sites and thinning sites in various quarters as small plots complicates the mechanization of labor-intensive operations, leading to low machine and equipment utilization rates. With intensive forest management, overcutting in coniferous stands occurs, and there is a frequent need to relocate logging and reforestation machinery from one cutting area to another.

Integrated forest operations necessitate new forms of work organization, specifically, the quarter-based method (Shirnin et al, 2001, Mokhirev & Rukomoinikov, 2022.). A forest quarter is a demarcated part of a forest tract, serving as a permanent accounting and management unit in the forests of the Russian Federation. During initial forest management planning, the territory of a forest enterprise is divided into forest quarters for forest inventory, organization, and management of forestry activities. In plain forests, quarters are typically rectangular or square, approximately equal in area, and separated by clearing lines. Forest quarters are subdivided into various forest inventory compartments. Each compartment is a separate part of a quarter which, upon reaching certain age and quality characteristics, is designated for cutting to conduct effective forestry activities (Rukomoynikov, 2015).

Analysis of literary sources demonstrates the importance of selecting the layout for the forest road network and skid trails on forest plots (George et al.

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2025, Tampekis, 2025., Zumbo et al., 2025). When using the quarter-based method, a significant portion of forest plots designated for cutting at one time is concentrated within a single quarter. This increases production concentration and creates conditions for transforming quarters (or blocks of quarters) into structural units for the organizational and economic development of the territory, complete with a network of haul roads, skid trails, technological corridors, and log yards.

2 MATERIALS AND METHODS

A number of methods for laying out main skid trails within a forest quarter have been developed. These methods involve dividing the forest quarter into sections formed by combining inventory compartments for intermediate and final fellings, with a comprehensive approach to the placement of main skid trails. The possibility of using these trails as skid roads at various stages of the forest quarter's development over different years is taken into account.

The task of improving accessibility to the combined compartments and ensuring the possibility of skidding wood from each section within the forest quarter is crucial for enhancing operational efficiency throughout all felling stages in the quarter. Developing a rational transport network helps reduce machine movement across the quarter and increases the productivity of logging machinery.

The proposed approach is based on the criterion of minimizing wood skidding cost, which is directly determined by the average skidding distance—a key indicator of the spatial efficiency of main skid trail placement.

3 RESULTS AND DISCUSSION

The layout of transport routes within a quarter significantly affects the cost of skidding wood, C (rub/m³).

$$C = \frac{C_m}{P_{cm}}, \tag{1}$$

where C_m - is the machine-shift cost of machines engaged in skidding, (rub/m³).; P_{cm} – is the shift productivity of the skidder, m³.

The primary factor affecting the shift productivity of skidders when comparing different transport route layouts in a quarter is the average skidding distance (Makarenko, 2018., Skrypnikov et al, 2016., Vadbolskaya & Azarenok, 2016). Analyzing known calculation methodologies from educational literature for the shift productivity of skidders, the main elements of their work cycle time that depend on the average skidding distance can be identified (Rukomojnikov et al, 2017). Thus, the cost of skidding wood can be represented as:

$$C = \frac{C_m}{P_{cm}} = \frac{C_m \cdot \left(T_o + \frac{\ell_{cp}}{\upsilon_{gx}} + \frac{\ell_{cp}}{\upsilon_{xx}} \right)}{3600 \cdot m \cdot \phi}, \tag{2}$$

where T_o - is the cycle time of the skidder, including collecting a turn, unloading, and piling it at the landing, sec; ℓcp - is the average skidding distance, m; υ_{gx}, υ_{xx} - are the average speeds of the machine during loaded skidding and empty return from the landing to the next collection point, respectively, m/sec; m - is the number of working hours per shift, h; ϕ - is the shift time utilization factor.

Considering the differences in the average skidding distance for various technological schemes of quarter development, this indicator is determined for different options of transport route layout within its territory.

The calculation scheme for determining the average skidding distance for the first proposed technology of quarter transport development, involving diagonal placement of main skid trails (Shirnin et al, 2004), is shown in Figure.1.

To determine the average skidding distance in the quarter, the quarter area is divided into geometric figures KDE, KEG, DOE, etc. The wood skidding work (load-distance) from these areas to the quarter boundary line is determined.

The lengths of the quarter sections can be calculated using the formulas:

$$D = \sqrt{A^2 + B^2}, \tag{3}$$

$$EG = EM = M = \frac{B}{2 \cdot \left(1 + \frac{2 \cdot B}{D}\right)}, \tag{4}$$

$$OE = \frac{2 \cdot M \cdot B}{D}, \tag{5}$$

where D - is the diagonal of the quarter, m.

The wood skidding work for the considered areas will then be:

$$R_{KEG} = \frac{q_i \cdot A \cdot B^2 \cdot D^2}{24 \cdot 10^4 \cdot \left(D + 2 \cdot B\right)^2}, \tag{6}$$

$$R_{KDE} = \frac{q_i \cdot A \cdot M \cdot \left(A + M\right)}{12 \cdot 10^4}, \tag{7}$$

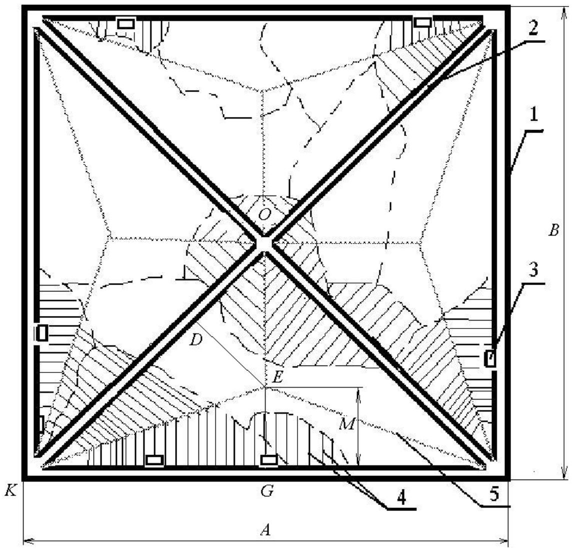

Figure 1: Calculation scheme for determining the average skidding distance from the quarter territory with diagonal placement of main skid trails: 1- quarter boundary line, 2 -- main skid trail, 3 -- landing, 4- secondary skid trail, 5 -- boundary of the area of influence.

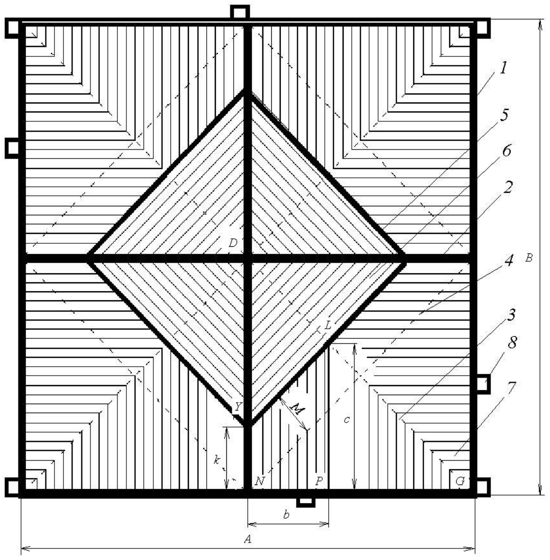

Figure 2: Calculation scheme for determining the average skidding distance from the quarter territory with perpendicular placement of main skid trails: 1- quarter boundary line, 2 -- main skid trail, 3 -- quarter diagonal, 4- auxiliary line for marking the technological corridor, 5 -- technological corridor, 6 -- area of influence bounded by the main skid trail, technological corridor, and quarter diagonal, 7 -- area of influence bounded by the quarter boundary line, main skid trail, and quarter diagonal, 8 -- landing.

$$R_{DOE} = \frac{q_i \cdot \left(D - A\right) \cdot M \cdot \left(D + 2 \cdot M + 2 \cdot A\right)}{24 \cdot 10^4}, \tag{8}$$

where q_i - is the total wood volume planned for harvesting in the considered area over all development periods of the quarter, accounting for the increase in wood stock between different felling cycles due to increment.

The calculation scheme for determining the average skidding distance for the second proposed technology of quarter transport development (Rukomojnikov, 2007, b), involving perpendicular placement of main skid trails parallel to the quarter boundary lines, is shown in Figure.2. To determine the average skidding distance in the quarter, the quarter area is divided into geometric figures. The wood skidding work from these areas to the quarter boundary line is determined.

The lengths of the quarter sections can be calculated using the formulas:

$$k = \frac{M \cdot \sqrt{B^2 + A^2}}{A}, \tag{9}$$

$$c=\frac{\left(\frac{M}{2\cdot M\cdot D+B^2}\cdot\left(\frac{D+B^2}{A}+\frac{2\cdot M\cdot B}{A}+2\cdot A\cdot M\right)+\frac{A}{2}\right)}{\frac{B}{\left(2\cdot M\cdot D+B^2\right)}\cdot\left(\frac{2\cdot D\cdot M}{A}+A\right)+\frac{B}{A}}, \quad (10)$$

$$b=\frac{A}{2}-\frac{B}{A}\cdot c, \quad (11)$$

The wood skidding work for the considered areas will then be:

$$R_{YNPL}=\frac{q_i\cdot b}{6\cdot 10^4}\cdot\left((k+c)^2-k\cdot c\right), \quad (12)$$

$$R_{LPG}=\frac{q_i\cdot(\frac{A}{2}-b)}{6\cdot 10^4}\cdot\left(c^2-c\right), \quad (13)$$

Using the methodology for calculating the skidding work for areas with diagonal trail placement, the skidding work for area YDL is determined under the condition that the quarter is square, i.e., A=B.

$$R_{YDL}=\frac{q_i\cdot b^2\cdot\left(b\cdot\sqrt{2}\cdot\left(2+\sqrt{8}\right)+6\cdot k\right)}{6\cdot 10^4} \quad (14)$$

The calculation scheme for determining the average skidding distance for the third proposed technology of quarter transport development (Rukomojnikov, 2007, a), involving curvilinear (arc-shaped) placement of main skid trails, is shown in Figure.3.

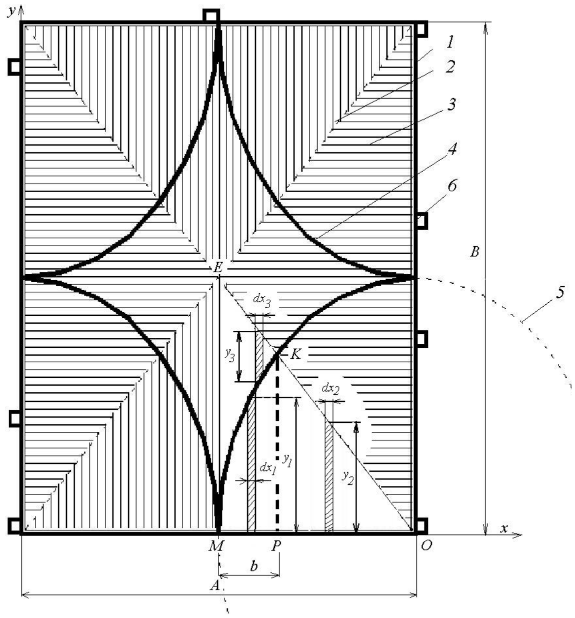

Figure 3: Calculation scheme for determining the average skidding distance during quarter development with curvilinear placement of main skid trails. 1 quarter boundary line; 2 -- quarter diagonal; 3 secondary skid trail; 4 -- main skid trail; 5 -- part of the ellipse for plotting the main skid trail path; 6- landing.

Consider area MKP, which is part of the area of influence where wood is skidded to the quarter boundary line, bounded by the main curvilinear skid trail, the quarter diagonal, and the quarter boundary line. The skidding work for moving wood from area MKP to the quarter boundary line MP is determined. An elementary area dx_1. Its area will be:

$$dS_1=y_1\cdot dx_1 \quad (15)$$

Considering the canonical equation of an ellipse, we get

$$\frac{4\cdot(A/2-x_1)^2}{A^2}+\frac{4\cdot y_1^2}{B^2}=1, \quad (16)$$

from which

$$y_1=\frac{B}{2}\sqrt{1-\frac{4\cdot(A/2-x_1)^2}{A^2}}, \quad (17)$$

Consequently, the equation for finding the area of figure MKP becomes

(18)

$$dS_1 = \frac{B}{2}\sqrt{1-\frac{4\cdot(A/2-x_1)^2}{A^2}}\cdot dx_1$$

The average skidding distance of wood from area dS_1 - via secondary skid trails to the quarter boundary line will be

$$l^n_{E(MKP)} = \frac{y_1}{2} = \frac{B}{4}\sqrt{1-\frac{4\cdot(A/2-x_1)^2}{A^2}}, \qquad (19)$$

The elementary skidding work on secondary trails for moving wood from area MKP will be

$$R^n_{MKP} = \frac{q_i}{10^4}\int_0^b \ell^n_{Э(MKP)}\cdot dS_1 = = \frac{q_i\cdot B^2}{10^4\cdot 8}\int_0^b (1-\frac{4\cdot(A/2-x_1)^2}{A^2})\cdot dx_1 = = \frac{q_i\cdot B^2(3\cdot A\cdot b^2-2\cdot b^3)}{12\cdot 10^4\cdot A^2} \qquad (18)$$

Considering that $\frac{B}{A} = \frac{y_2}{\frac{A}{2}-b}$, we get

$$y_2 = \frac{B}{A}(\frac{A}{2}-b) \qquad (21)$$

Equating $y_1 = y_2$, we get

$$b = \frac{A}{2}\left(1-\frac{\sqrt{2}}{2}\right) \qquad (22)$$

Substituting the obtained value of b into formula (20), we get

$$R^n_{MKP} = \frac{q_i\cdot B^2\cdot A}{192\cdot 10^4}\cdot(8-5\sqrt{2}). \qquad (23)$$

To determine the skidding work for moving wood from part PKO to the quarter boundary line PO, the following mathematical dependencies can be used:

$$R^n_{PKO} = \frac{q_i\cdot B^2}{6\cdot 10^4\cdot A^2}(A/2-b)^3 \qquad (24)$$

Substituting the value of b from formula (22), we get

$$R^n_{PKO} = \frac{q_i\cdot A\cdot\sqrt{8}}{384\cdot 10^4} \qquad (25)$$

To determine the skidding work for moving wood from area MEK, calculations are performed separately for the work on secondary trails and on the main curvilinear skid trail, considering the difference in skidding equipment speeds on them.

An elementary area of length dx_3 - is highlighted within the section. Its area is

$$dS_3 = y_3\cdot dx_3. \qquad (26)$$

where

$$y_3 = y_2 - y_1 \qquad (27)$$

The average skidding distance of wood from area dS_3 -via secondary skid trails to the main skid trail will be

$$l^n_{E(MEK)} = \frac{y_3}{2}. \qquad (28)$$

Then the elementary skidding work on secondary trails for moving wood from area MEK will be

$$R^n_{MEK} = \frac{q_i}{10^4}\int_0^b l^n_{E(MEK)} = = \frac{q_i}{2\cdot 10^4}\int_0^b \left[\frac{B}{A}\left(\frac{A}{2}-x\right) - \frac{B}{2}\sqrt{1-\frac{4\cdot(A/2-x)^2}{A^2}}\right]^2\cdot dx_3 = = \frac{q_i\cdot B\cdot A}{48\cdot 10^4}\left(3-2\sqrt{2}\right) \qquad (29)$$

The average skidding distance along main skid trails can be calculated approximately, with sufficient accuracy for practical calculations. Using the formula for the length of a parabolic (elliptical) arc segment, the length of the main skid trail within one area of influence is determined:

$$\breve{L} = y_2\left[1+\frac{2}{3}\left(\frac{b}{y_2}\right)^2-\frac{2}{5}\left(\frac{b}{y_2}\right)^4\right] \qquad (30)$$

Then the skidding work for moving wood along the main skid trail is approximately equal to

$$R^{n}_{MEK} = \frac{q_i}{10^4}\int_0^b \ell^{M}_{E(MEK)} \cdot dS_3 = \tag{31}$$

$$= \frac{q_i}{10^4}\int_0^b \left[\begin{array}{c} \frac{\breve{L}\cdot x}{b}\cdot\frac{B}{A}\cdot\left(\frac{A}{2}-x\right)- \\ = \dfrac{\breve{L}\cdot B^2\cdot\sqrt{1-\frac{4\cdot\left(A/2-x\right)^2}{A^2}}}{4\cdot\left[\frac{B}{2}\cdot\sqrt{1-\frac{4-\left(A/2-b\right)^2}{A^2}}\right]} \end{array} \right]\cdot dx_3 =$$

$$= \frac{\breve{L}\cdot B\cdot A\cdot q_i}{48\cdot 10^4}\cdot\left(10-7\sqrt{2}\right)$$

Thus, the skidding work for moving wood from the area of influence bounded by the curvilinear main skid trail, the quarter diagonal, and the quarter boundary line will be

$$R_1 = R^{n}_{MKP} + R^{n}_{PKO}, \tag{32}$$

and the skidding work from the area of influence remote from the quarter boundary line is equal to

$$R_2 = R^{n}_{MEK} + R^{m}_{MEK} \tag{33}$$

The skidding work for moving wood to the quarter boundary lines from other areas of the quarter can be determined similarly to the considered areas, using the proposed dependencies.

Based on the calculations performed, the average skidding distance from the quarter territory with different placements of main skid trails can be found using the formula:

$$l_{cp} = \frac{\sum_{i=1}^{n} R_i}{Q_k} \tag{34}$$

where i=1....n is the number of areas within the quarter; Q_k- is the total wood volume planned for harvesting within the quarter over all felling cycles, accounting for wood increment between fellings, m^3.

$$Q_k = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{n}\frac{S_i\cdot q_i}{10^4} \tag{35}$$

where S_i is the areas of the influence zones of the combined compartments within the quarter, m^2. For example:

$$S_{MEK} = \frac{0,43\cdot A\cdot B}{16} \tag{36}$$

$$S_{PKO} = \frac{B\cdot A}{16} \tag{37}$$

$$S_{MKO} = \frac{0,57\cdot A\cdot B}{16} \tag{38}$$

4 CONCLUSIONS

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A comparative analysis of the considered technological schemes showed that each option has its own area of economic feasibility, depending on the size and configuration of the quarter, as well as the volume and distribution of forest resources. The curvilinear option, although the most complex to design, potentially minimizes the average skidding distance by better adapting the trail route to the shape of the quarter and its areas of influence. The perpendicular and diagonal schemes may be more efficient in terms of reducing capital costs for development The following tasks were formalized and solved in this work:

Calculation schemes and analytical dependencies were developed for determining the average skidding distance for three fundamentally different options for placing main skid trails: diagonal, perpendicular, and curvilinear (arc-shaped).

For each option, a methodology was defined for calculating the wood skidding work, involving the division of the quarter territory into geometric areas of influence, allowing for a highly accurate assessment of transport costs.

The proposed model accounts for the dynamic nature of quarter development, including planned harvesting volumes throughout all felling stages, considering wood increment.

The practical significance of the work lies in the fact that the presented materials and methodologies provide forest management engineers and technologists with a tool for the quantitative justification of decisions made at the planning stage. Using this approach allows for a transition from an intuitive choice to a scientifically based design of the transport network, ultimately leading to: reduced operational costs in logging through the optimization of skidding operations; increased productivity of skidding equipment; reduced negative impact on the forest environment by minimizing excessive density of transport routes and their rational placement. The implementation of the proposed methodology for economic comparison in forest management practice will contribute to enhancing the overall efficiency and sustainability of forestry.

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