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Mathematical Modeling of Forwarder Operation When Collecting Logs in the Forest Swath

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Abstract: Optimization of the machines allows you to increase their productivity and reduce the labor costs for performing individual elements of the technological cycle of their work in the forest. In this regard, the authors offer theoretical studies that take into account the peculiarities of the work of one of the most popular logging machines today, namely, a machine for collecting and forwarding logs (forwarder). The article discusses the technological features of the functioning of these machines, identifies ways to reduce the cost of collecting logs, justifies the rational width of apiaries, which allows collecting logs with a minimum number of movements between work positions. The main purpose of the study is to substantiate the mathematical dependence for determining the rational values of such interrelated parameters of the forwarder's operation as the distance between the working positions of collecting logs and the width of apiaries. The authors propose an analytical approach to solving the problem. On the basis of the standard technological scheme of the harvester's movement through the swath, geometric regularities of the trajectory of the manipulator movement, dimensional characteristics and location of the prepared logs are revealed. As a result of the work, mathematical dependencies are constructed that make it possible to determine the rational values of the desired parameters. The results can be used by research organizations in planning the production process of logging operations. The introduction of author's recommendations into production will contribute to improving the efficiency and operation of forestry equipment.

Keywords: forwarder; forest swath; log; log forwarding; logging; manipulator

1 INTRODUCTION

In the normal Nordic harvesting tree stems are processed into logs at the cutting area. Usually 2 machines are used: harvester and forwarder, or felling of trees, pruning of branches and bucking are carried out by a feller with a chainsaw [20, 30, 35]. Thus, any of the variants of the technological process of harvesting logs of one of the machines of the technological process is a forwarder. This causes increased interest in modeling the technological process of the forwarder from scientists around the world [6, 10, 13, 15, 22, 26, 36].

The accuracy of the performance assessment using the obtained models should be sufficient to simulate production processes at various cutting areas. The research [21] proves that the technology of forwarder operators has become more labor-intensive in recent years, despite the successes achieved in the design of logging equipment. The species diversity of logs has increased during their sorting during the forwarder loading process due to more specific product requirements. The number of scattered piles is bunched has increased when unloading logs at loading points. This created more difficult working conditions when loading and unloading logs with a forwarder.

When choosing machines and mechanisms for the implementation of logging operations, as well as the organization of the production process, it is necessary to take into account many different factors. Optimization of the machines allows you to increase their productivity and reduce the labor costs for the implementation of individual elements of the technological cycle of their work in the forest [17, 27-29]. Focusing the attention of the readers of the article on the forwarder, as a machine that is one of the most popular by loggers around the world today, we can say that its productivity largely depends on the average volume of the stick, the distance of forwarding logs, the standing volume in the forest cutting area, the distances between forest swaths and the qualifications of the machine operator [16, 18, 23, 24, 31, 32]. According to the authors, the issue of optimizing these parameters during the operation of machines for harvesting logs is currently not fully studied. In this regard, the authors offer additional theoretical studies, teaching the features of the work of these machines in the forest.

The purpose of the study is to substantiate the mathematical dependence for determining the rational values of such interrelated parameters of the forwarder's operation as the distance between the working positions of collecting logs and the width of forest swathes.

2 MATERIALS AND METHODS

The purpose of the study is to substantiate the rational values of such interrelated parameters of the forwarder's operation as the distance between the working positions of collecting logs and the width of forest swathes.

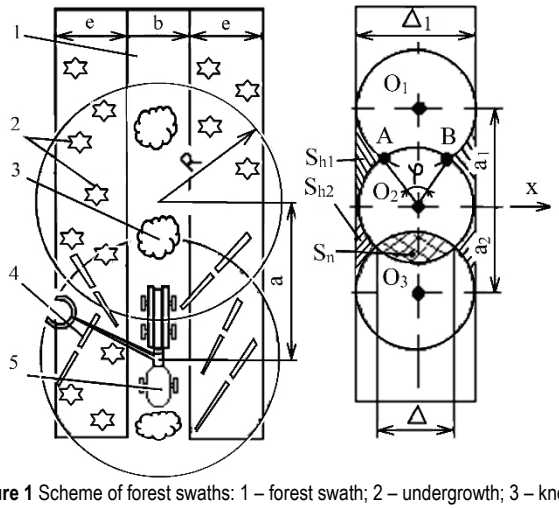


Figure 1 Scheme of forest swaths: 1 – forest swath; 2 – undergrowth; 3 – knots; 4 – logs; 5 – forwarder. Source: Compiled by the authors.

To analyze the work of the forwarder, the collection of logs used scheme, presented in Fig. 1a. On the forest swath with a width of Δ, the feeling of all trees intended for logging

is carried out, with the abandonment of part of the stand and undergrowth. After pruning the branches from the trees, they are laid on skidding track. The logs after cutting into lengths also remain on skidding track. They are collected and laid by the manipulator on the freight platform of the forwarder.

The time to collect a bundle of logs depends on the number of working positions. In turn, the number of working positions is inversely proportional to the area processed by the forwarder from one position. The scheme for calculating the area is presented in Fig. 1b.

If the width of the forest swath is $\Delta_1 = 2R$, and the distance between the working positions O_1 and O_2 is a_1, then the untreated area S_{h1} appears on the forest swath. The greater the distance between the working positions, the larger the uncultivated area of the forest swath. Reducing the share S_h is possible in two ways: reducing the width of the forest swath being processed $\Delta_1 \rightarrow \Delta$; reducing the distance between working positions $a_1 \rightarrow a_2$. In the second case, there is an area of the double segment S_n, which can be processed from both the second and third working positions. One hundred percent processability of the forest swath can be achieved only with simultaneous accounting of the listed methods.

The width of the forest swath Δ being developed can be found using the circle equation:

$$(x-a)^2 + (y-b)^2 = R^2, \tag{1}$$

where, a and b are centers of circles.

$$\begin{cases} x^2 + y^2 = R^2 \\ x^2 - (y-a)^2 = R^2. \end{cases} \tag{2}$$

Having solved the system of equations for two given circles with centers O_1 (0, 0) and O_2 (0, a) and radius R, we find the coordinates of points C, D of the intersection of circles:

$$y = \frac{a}{2}, \tag{3}$$

$$x = \pm\frac{\sqrt{4R^2 - a^2}}{2}. \tag{4}$$

When using a forwarder for forwarding, it must be borne in mind that in order to ensure a reliable capture of logs, its dragging and laying to the forwarder's cargo platform, it is enough that only a part of it is in the range of the manipulator, the length of which guarantees the possibility of accurate guidance of the grab and the capture of the log. Taking into account the different location and angle of felling of trees, the scheme for calculating the area processed by the forwarder from one working position can be depicted in the form of Fig. 2. This figure shows the areas processed at the minimum and maximum angles of felling trees in forest swathes. Analyzing the data of the scheme, it can be concluded that the treated area, on which the logs obtained by cutting the sticks of trees felled at the same sharp angle to the axis of the forest swath are located, will have an oval shape (Fig. 2a and 2b). Combining several design schemes that take into account the maximum and minimum angles of felling trees, and analyzing several adjacent working positions simultaneously (Fig. 2c), it can be noted that the width of the tape on which the collection of all logs is ensured, regardless of the angle of fall of the tree and the absence of untreated areas is provided, will be equal to

$$\Delta = \sqrt{4R^2 - a^2} + L, \tag{5}$$

where is $L = 2(l_{cop} - j_{cop}) \cdot \sin c$.

Where c - the minimum angle of felling of trees located on the border of the forest swath, hail; j_{cop} – the length of the part of the log, which must be in the zone of action of the manipulator to ensure a reliable capture of the log, m; l_{cop} – length of the log, m.

The performance of the forwarder is significantly affected by the time of collection of a bundle of logs, which can be represented in the form of equation:

$$T_1 = \sum_{g=1}^{z} \frac{M}{V_{cg}} \cdot \omega \cdot t_{dzy} + \frac{M \cdot \sum_{g=1}^{z} \frac{1}{\omega}\left(t_{yp} + \frac{a}{\vartheta_{pn}} + t_{ym}\right) \times 10^4}{q \cdot a \cdot k_i \cdot z \cdot \left(\sqrt{4R^2 - a^2} - L\right)}, \tag{6}$$

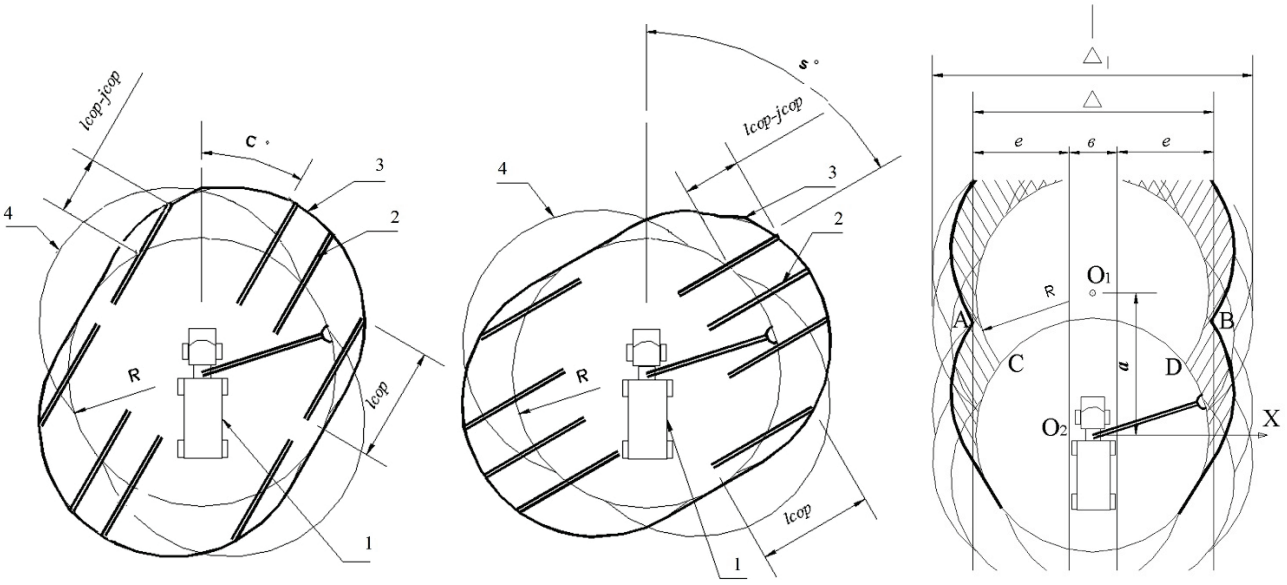
where ω – the share of the component of a certain variety group during sorting at the cutting site in the total volume of harvested wood; V_{cg} – the average volume of the log of g – component, m^3; M – the average volume of bundle of logs, m^3; z – the number of sorting components when collecting a bundle of logs; t_{dzy} – the time of capturing the log and stacking it on the cargo platform, sec; t_{yp}, t_{ym} – respectively, the time of installation of technological equipment in the working position and vice versa, sec.

By changing the distance between the work positions, it is possible to reduce their number, which is necessary to collect a bundle of logs, reduce the cycle time of work and, as a result, increase the replaceable performance of the forwarder. The optimal valuea will be the one in which the time to collect a bundle of logs is minimal. Having found the derivative of the obtained expression and equating it to zero, after the transformations we get:

$$\frac{d \cdot T_1}{d \cdot a} = \frac{M \times 10^4}{q \cdot k_i \cdot \left(\sqrt{4R^2 - a^2} - L\right)} \cdot \left(\frac{t_{pm} + \frac{a}{\vartheta_{pn}}}{\left(\sqrt{4R^2 - a^2}\right) \cdot \left(\sqrt{4R^2 - a^2} - L\right)} - \frac{t}{a^2} \right), \tag{7}$$

$$4L^2R^2t_{pm}^2\vartheta_{pm}^2 - 16R^4t_{pm}^2\vartheta_{pm}^2 - L^2t_{pm}^2\vartheta_{pm}^2a^2 + \\ +16R^2t_{pm}^2\vartheta_{pm}^2a^2 + 8R^2t_{pm}\vartheta_{pm}a^3 - 4t_{pm}^2\vartheta_{pm}^2a^4 - \\ -4t_{pm}\vartheta_{pm}a^5 - a^6 = 0 \quad (8)$$

where t_{pm} is the time of transfer of technological equipment from the working position to the transport one and vice versa, sec.



a) b) c)

Figure 2 Calculation schemes for determining the optimal width of the forest swath and the distances between the working positions of the forwarder: a) at the minimum angle of felling of trees (co) located on the border of the forest swath; b) at the maximum angle of felling of trees (so); c) a combined scheme that takes into account the different arrangement of logs in the forest swath: 1- forwarder; 2 – log; 3, 4 – zones of action of the manipulator at different angles of incidence of the tree; the direction of hatching corresponds to the direction of felling trees. Source: Compiled by the authors.

3 RESULTS

To find the optimal distance between the working positions, we will solve this equation using Newton's method proposed for solving equations of *n*-degree. Since the distance between the working positions is within $R < a < 2R$, then as the first approximation of the desired value of the optimal distance between the working positions, we take $a = 1.4R$.

With further calculations, we will get

$$a = 1.4R - \frac{t_{pm}\vartheta_{pm}R\left[t_{pm}\vartheta_{pm}(1.02L^2 - 0.0032R^2) + 0.21952R^3\right] - 3.76477R^5}{t_{pm}\vartheta_{pm}\left[t_{pm}\vartheta_{pm}(0.448R^2 - 1.4L^2) - 14.896R^3\right] - 16.1347R^4} \quad (9)$$

To find the desired value with a sufficient degree of accuracy for practical calculations, we will use the equation

$$a_0 = a - \frac{f(a)}{f'(a)} \quad (10)$$

or

$$a_0 = a - \frac{t_{pm}\vartheta_{pm}\left\{t_{pm}\vartheta_{pm}\left[a^2\left(4(4R^2 - a^2) - L^2\right) + 4R^2(L^2 - 4R^2)\right] - 4a^3(a^2 - 2R^2)\right\} - a^6}{t_{pm}\vartheta_{pm}\left\{2t_{pm}\vartheta_{pm}\left[a\left(8(2R^2 - a^2) - L^2\right)\right] - 4a^2(5a^2 - 6R^2)\right\} - 6a^5} \quad (11)$$

With the subsequent replacement of a with a_0, a more accurate value of the optimal distance between the forwarder's working positions can be obtained, although in order to find the optimal a_0, the accuracy of which is sufficient for practical purposes, additional substitutions of the a_0 instead of the anot required instead. By substituting the resulting value into the equation for calculating Δ, you can calculate the optimal value of the width of the forest swath.

Calculations were carried out for the following conditions: $q = 60$ m^3/ha; $V_{cg} = 0.3$ m^3; average length of the log 6 m; $t_{pm} = 8$ sec; $c = 30°$; $\vartheta_{pm} = 1$ m/sec; $\omega = 1$.

For the Valmet 860 forwarder with the technical parameters marked in the reference data $R = 7.2$ m; $M = 14$ m^3 the following results were obtained: $L = 5$ m; $a = 9.38$ m; $a_0 = 9.1$ m; $\Delta = 16.1$ m.

After substituting the parameters of the various

machines, the desired value of the optimal distance between the operating positions was 9.1 for the Forwarders Valmet 860, Ponsse S15, Valmet 840, Tumberjack 1010B, Farmi Trak 575F, LT-189 and Terri 2040D, respectively, 12.8, 9.5, 12.7, 10.9, 7.3, 6 m.

In order to solve the question of finding the optimal distance between the working positions, determining the effect of its change and checking the adequacy of the results obtained, graphs were drawn up of the dependence of the time of the collection cycle of a bundle of logs on the distances between the working positions and the forwarder (Fig. 3), which confirmed the optimal values of a_0.

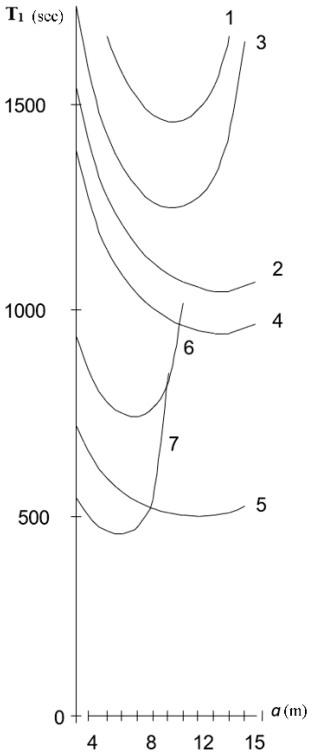


Figure 3 Graphs of the dependence of the time of the cycle of harvesting bundle of logs of timber on the average distance between the working positions of the forwarder (1 - Valmet 860; 2 - Ponsse S15; 3 - Valmet 840; 4 - Tumberjack 1010B; 5 - Farmi Trak 575F; 6 - ЛТ-189; 7 - Terri 2040D). Source: Compiled by the authors.

4 DISCUSSION

Accurate predictions in forest operations can be used towards effective planning, costing, and maximizing the productivity of machines in mechanized cut-to-length harvesting [5]. Many scientists have been analyzing the factors affecting the forwarder's work. The forwarder's performance was evaluated based on modeling of individual elements of the cycle time. The main factors affecting productivity were recognized as: the size of the logs, the distance of the forwarding, the volume of logs forwarding at a time [10]. It is determined that the type of cutting works (thinning or final felling) has an important influence on the forwarder's performance [11, 12, 39]. It is noted that, regardless of other factors, the forwarder's operating time increases dramatically with increasing forwarding distance [38]. These observations suggest that maximization of payload and optimization of timber extraction distance are more crucial for economic forwarding.

At the same time, the analysis of the work of forwarders conducted in the [14], shows that time consumption per load was more strongly associated with loading drive distance than with extraction distance, indicating that the relevance of extraction distance as a main indicator of forwarding productivity should be re-considered. The study of these authors increases the importance of analyzing the forwarder's work during the loading of logs. In the article [4] an assessment of the effectiveness of log forwarding using various techniques and mechanisms for felling and cross-cutting was carried out. The main task of these researchers was to determine the effect of the relative position of the logs on the speed of the forwarder manipulator during loading. The initial hypothesis that the location of logs in the forest swath during loading has an important effect on forwarder productivity has been confirmed. Loading operations on portages in the forwarder's technological cycle are well analyzed in the article [25]. The operation cycle of the forwarder manipulator on the fiber was divided into 21 loading processes. The impact of the technological features of the work during the implementation of each of the operations on the efficiency of the entire cycle of operation of this logging equipment has been assessed. Correlations have been found demonstrating the influence of a number of technical indicators on empty and loaded movements of the forwarder manipulator when loading logs.

Thus, the noted studies confirm that the process of collecting logs is an important element of the forwarder's work cycle time and should be comprehensively considered when modeling the technological process.

In addition, scientists noted that an important role in optimizing the process of log forwarding is played by the correct mathematical justification of the number of transport routes in the forest. With an increase in the number of forwarding roads, the forwarder's productivity increases, but at the same time this leads to an increase in the cost of transport routes in the forest. This analysis is based on minimizing the amount of financial costs for the construction and maintenance of forest roads, as well as the removal of logs and damage from the reduction of the area covered by forest [1, 2, 7, 8, 19, 33, 40]. As a result of these studies, the effect of the distance between the forwarding roads on the forwarder's performance has been proven. The issue of substantiating the number of skidding roads has been considered in detail from an economic point of view, but these scientific works do not address the issues of expediency of changing the technology of forwarder movements when changing the distances between forwarding roads. The next step towards improving the efficiency of log forwarding machines may be studies determining the effect of the distances between the forwarding roads on the choice of an effective forwarder technology when collecting logs.

It can be noted that scientists from different countries have carried out a significant amount of research on the analysis of the forwarder's work on the territory of various cutting areas. However, in previous studies, the influence of

the density of the forwarding road network, and, consequently, the width of forest swathes on the expediency of changing the technology of the forwarder when collecting logs has not been sufficiently studied.

Thus, the studies by other researchers of the work of logging machines do not contradict the conclusions and recommendations obtained in our article and emphasize the importance of choosing the correct parameters of the machine. In particular, the studies [36] offer a variant of substantiation of the algorithm of work and the search for rational distances between the working positions of the harvester on the basis of simulation modeling systems, including a sequence of actions that uses all the technical and technological capabilities of the machine and ensures an increase in its efficiency. However, simulation modeling, increasing the accuracy and reliability of calculations, does not allow the researcher to quickly analyze individual parameters of the machine without the use of specialized software tools.

In the work [9] an analytical calculation of the optimal parameters of forest swaths is carried out, as well as the method of their experimental determination in various natural and production conditions by methods of simulation modeling. The equations obtained in the work provide a maximum working area, and hence the maximum volume of a bundle of logs formed in the parking lot. However, the optimization of the considered indicators is carried out on the basis of the maximum area processed from one working position of the machine and does not take into account such important elements of the cycle time for forwarders as the time spent on moving between working positions, and the time of transferring equipment from the transport position to the working position and vice versa.

The noted shortcomings are absent in the work [3], but these studies are focused on the calculation of the operating parameters of forest swaths when using machine felling of wood, which has significant differences from the technology where the leading machine is a forwarder.

5 CONCLUSION

Therefore, we demonstrated in this study that the number of roads per unit area affects the technological factors of the forwarder's work.

Analyzing the equation obtained in the article, it can be concluded that the optimal distance between the working positions depends on the technical characteristics of the machine, the possibility of their implementation, the qualifications of the operator and the technology of work, and can be calculated in advance for any brand of machine engaged in the operation of collecting and forwarding logs.

One of the elements of the novelty of the work performed is the possibility of simultaneously taking into account the technical and technological parameters of the forwarder's work when collecting logs in the forest swath. The resulting mathematical dependence allows us to take into account the characteristic conditions of the use of machines. Namely, the various characteristics of the cutting areas being developed, the technological process, the method of developing the cutting area, the angle of felling of trees located on the border of the forest swath, and to obtain adequate results.

Comparison of the labor costs for collecting a bundle, calculated taking into account the values obtained according to the mathematical dependence proposed in the article, with the calculated labor costs possible with incorrectly selected values of a and Δ, allows us to conclude that the correct choice of technological parameters of the forwarder's operation can reduce the cycle time for collecting a bundle of logs by 20%. The introduction of recommendations for determining the optimal values a and Δ will increase the efficiency of the operation of forwarders.

Acknowledgments

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