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Simulation Modeling of Time for Moving a Fallen Tree by Harvester to the Zone of Its Bucking

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Abstract

The aim of the research was to create a mathematical dependence to justify the labor costs of moving a fallen tree by harvester to the zone of its bucking, depending on the variety of values of natural factors characterizing the operation of the harvester during the partial cut of the forest. For this research, the computer simulation model of the technological process of the forest harvester was created. Production experiments were carried out to test the model. The computer experiment was implemented on the model, and regression dependence was obtained. The results of this study showed that the relationship between the residual density of plantings and the execution time of the moving operations using regression dependence. The multiple coefficients of determination of the nonlinear model was 0.845. This value indicates that the change in the average time of moving a fallen tree to the zone of its bucking depends on changes in the factors included in the regression model, and this dependence is not accidental. The results can be used by research organizations when planning the production process of logging operations.

Keywords: Log, labor norming, working position, harvesting, simulation modeling, statistics.

1. Introduction

When choosing effective logging systems, forestry managers should take into account the interaction of factors of plantings, harvesting, and machines. These solutions are often complex, given the range of available equipment, and the desire to use new logging schemes without collecting production data on this type of work in the forest. Factors such as the size of the tree being removed, the initial and residual density of the tree plantation, the size of the equipment and working methods can affect the production and cost of the system. Currently, there are many researches available that studies the process of harvesting wood. For experimental researches with the reliability necessary for the researcher, it is necessary to set up a number of experiments with proof of the reproducibility of the conducted studies. However, full-scale industrial research is hindered by the complexity and cost of reproducing experiments in various conditions. In addition, some influencing factors, such as the volume of the tree, the proportion of the felled component of wood from one working position, and many other parameters are difficult to challenge in the forest. Computer modeling combined with the limited data required for its implementation allows us to overcome many of these disadvantages.

The main leaders in the development of computer support for managerial decision-making in the rationing of labor in logging operations, in particular simulation systems, are North America (Johnson and Biller, 1973; Killham, 1975; Webster, 1975; Bare et al., 1976; Bradley et al., 1976; O'Hearn et al., 1976; Fisher and Gochenour, 1980; Goulet et al., 1980; Winsauer, 1980; Stuart, 1981; Garbini et al., 1984; Greene et al., 1987; Kellogg and Bettinger, 1994; McNeel and Rutherford, 1994; Randhawa and Scott, 1996; Aedo-Ortiz et al., 1997; Wang et al., 1998; Stampfer and Henoch, 1999; Hartsough et al., 2001; Yaoxiang, 2005), Finland (Nurminen et al., 2006; Asikainen, 2010), - Sweden (Eliasson and Lageson, 1999; Bergström et al., 2007; Lindroos, 2008; Sängstuvall et al., 2012), Central Europe (Italy, Austria) (Spinelli and Visser, 2008), and Russia (Shirnin and Onuchin, 2003; Sokolov and Osipov, 2017; Chaika and Fokin, 2018; Chernik, 2020). Simulation models provide valuable, flexible tools for evaluating various capabilities of the timber industry, such as concepts of the development of logging machines, and therefore arouse increased interest among scientists from various countries.

2. Materials and Methods

2.1. Study Area

The research aimed to develop a mathematical model that could accurately predict the labor cost of moving a fallen tree by harvester to the zone of its bucking. This

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model was designed to consider a wide range of natural factors that influence the operation of the harvester during partial cut of forest, setting it apart from existing research in the field.

The research was implemented in several stages. At the first stage, the simulation model was developed based on the Anylogic simulation system (The AnyLogic Company, 2024). A more detailed description of this simulation model can be found in the earlier article (Rukomoynikov et al., 2022a; Rukomojnikov et al., 2022b).

In the second stage, the created simulation model underwent production testing due to observations of the harvester Silvatec 8266TH. Supervising the operation of the Silvatec 8266TH harvester was carried out under the control of an experienced operator with more than 5 years of experience. The width of the apiaries was 15 meters. The sections of apiaries analyzed during the experiment had a length of 100 meters. During experimental studies, 9 apiaries were conducted, characterized by different stocks of wood. All apiaries were developed sequentially during the week, with comparable weather and natural conditions. A more detailed description of the production experiment can be found in the previously published article (Rukomojnikov et al., 2024). Research has shown that the simulation model adequately reflects the production process, and the results obtained with its help demonstrate with a sufficiently high degree of accuracy the results of the harvester's work with all logging methods.

In the third stage, the most critical factors characterizing the natural conditions of logging operations in the cutting area were selected. In the fourth stage, experiment was conducted on the created simulation model, taking into account the real statistical data obtained at the previous stages of the study. The data collection process was thorough, ensuring the accuracy and reliability of our findings. For this purpose, a four-factor experimental plan was drawn up. The factors studied during the simulation experiment varied at four levels of variation with a complete search of options. The parameters were varied in the ranges presented in Table 1.

3. Results

The time of movement of a fallen tree was fixed from the moment the tree was separated from the stump until the beginning of bucking of the tree. With the created model, work area in the zone of operation of the harvester manipulator was divided into several sectors.

When working in the first sector, located in front of the harvester, the forwarding trail was cleared. The logs harvested, in this case, were laid parallel to the forwarding trail near the machine. When felling trees in the sectors located to the left of the harvester, they were moved to the area to the right of the harvester. When felling trees in the sectors located to the right of the harvester, the fallen trees were moved for subsequent processing to the area to the left of the harvester (Figure 1).

Table 1. The range of variation of factor features during the implementation of the simulation of the harvester operation.

	Symbol	Variation levels			
		1	2	3	4
Total stand of timber, m^3/ha	Q	50	120	190	260
Proportion of component to be cut down	k_i	0.2	0.4	0.6	1
Amount of large brushwood per hectare, pcs/ha	$K_п$	0	150	300	450
Tree volume, m^3	$V_в$	0.2	0.7	1.2	1.7

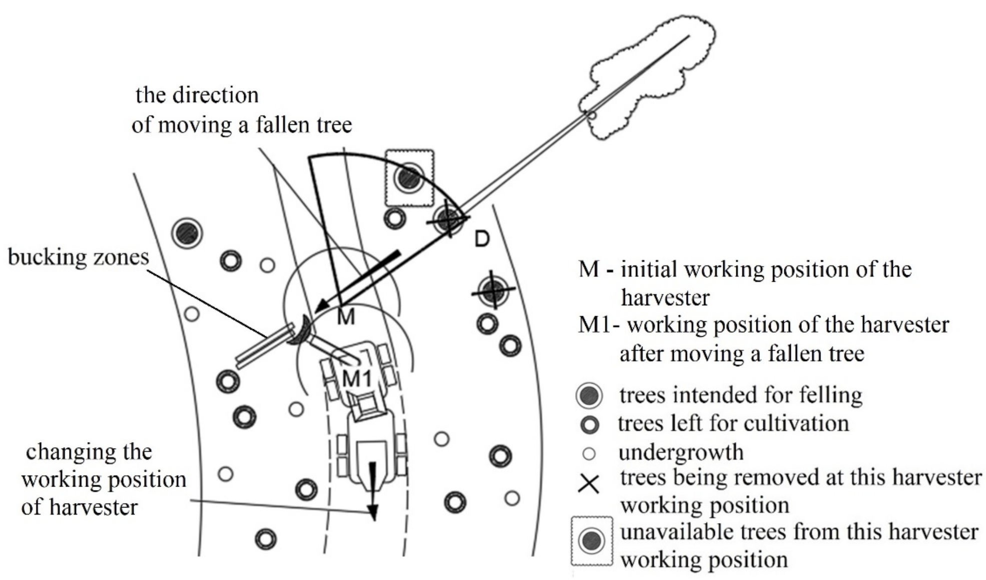

Figure 1. The scheme of movements of the harvester when moving a fallen tree to the zone of its bucking

The use as an effective indicator of the average time of moving a fallen tree to the zone of its bucking with and without adjustment of the harvester's working position during the movement (t_p, sec) allowed us to obtain the following regression dependence:

$$t_p = c_0 + Q \cdot (c_1 + c_5 \cdot k_i + c_6 \cdot K_п + c_7 \cdot V_в) + k_i \cdot (c_2 + c_9 \cdot V_в) + K_п \cdot (c_8 \cdot k_i + c_3) + V_в \cdot (c_4 + c_{10} \cdot K_п) + c_{11} \cdot {k_i}^2 + c_{12} \cdot {K_п}^2 + c_{13} \cdot {V_в}^2 \quad (1)$$

The results from the coefficients of the regression equation and their confidence intervals are shown in Table 2. The results indicate the statistical significance of the coefficients included in the regression model. The calculated indicator P is the value of all coefficients less than the level of statistical significance (0.05). The critical value of the Student's t-test, equal to 1.96, is less than the calculated values of this indicator for any of the regression equation coefficients. All the found values of standard errors are less than the modules of the values of the coefficients of the final equation corresponding to them.

The multiple coefficients of determination R2 of the nonlinear model was 0.845. This value indicates that the change in the average time of moving a fallen tree to the zone of its bucking depends on changes in the factors included in the regression model, and this dependence is not accidental.

The calculated indicators of statistical processing of the average time of moving a fallen tree to the zone of its subsequent processing, presented in Table 3, confirm the reliability of the model. The calculated value of the significance level is less than the set value of 0,05, providing further reassurance about the robustness and trustworthiness of the model.

The normal probabilistic graph (Figure 2) showed no systematic deviations in regression modeling results from the theoretical normal line. All points (residuals) on the graph are close to the line expected for normally distributed residuals. The histogram of the remains shown in Figure 3 also allows us to visually confirm the proximity of the distribution of the remains of the average time of moving a fallen tree to the zone of its bucking to the normal distribution law.

Figure 4 shows the comparative analysis of predicted and observed values. Figure 5 shows the graph of predicted values and residuals. The analysis of the graphs allows us to note only a slight discrepancy between the results recorded by the simulation and regression models. Graphs make it possible to state the adequacy of the regression equation to the results of computer modeling.

Table 2. Checking the statistical significance of the coefficients of the regression equation when justifying the average time of moving a fallen tree to the zone of its subsequent processing.

	Estimate	Std.Err	t	P-value	-95% CL	+95% CL
c_0	7.56201	0.32922	22.96954	0.0000	6.91262	8.21140
c_1	0.015856	0.001895	8.365882	0.0000	0.012118	0.019595
c_2	10.59971	0.73579	14.40581	0.0000	9.14834	12.05109
c_3	0.007483	0.001009	7.418155	0.0000	0.005493	0.009473
c_4	-4.3837	0.3664	-11.9640	0.0000	-5.1065	-3.6610
c_5	-0.00942	0.00180	-5.22596	0.0000	-0.01298	-0.00587
c_6	-0.00001	0.00000	-3.99362	0.0001	-0.00002	-0.00001
c_7	-0.00407	0.00132	-3.09271	0.0023	-0.00667	-0.00148
c_8	0.00794	0.00073	10.81634	0.0000	0.00649	0.00938
c_9	2.572018	0.265061	9.703492	0.0000	2.049177	3.094858
c_{10}	0.002222	0.000465	4.782194	0.0000	0.001306	0.003139
c_{11}	-9.4500	0.5136	-18.3987	0.0000	-10.4631	-8.4369
c_{12}	-0.000004	0.000002	-2.59772	0.0101	-0.000007	-0.000001
c_{13}	1.045626	0.184137	5.678521	0.0000	0.682411	1.408841

Table 3. Analysis of variance in substantiating the average time of moving a fallen tree to the zone of its subsequent processing

	Sum of Squares	df	Mean Squares	F-value	p-value
Regression	27584.40	14.00	1970.314	7365.465	0.00
Residual	50.83	190.00	0.268		
Total	27635.22	204.00			

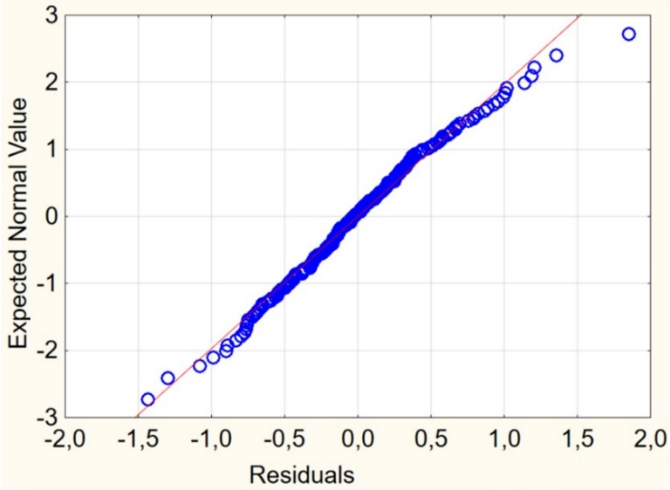

Figure 2. Normal probabilistic graph when justifying the average time of moving a fallen tree to the zone of its subsequent processing

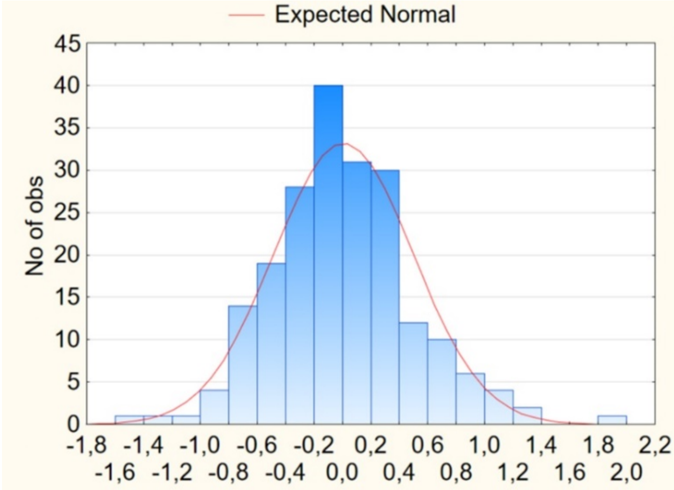

Figure 3. Histogram of the distribution of residues when justifying the average time of moving a fallen tree to the zone of its subsequent processing

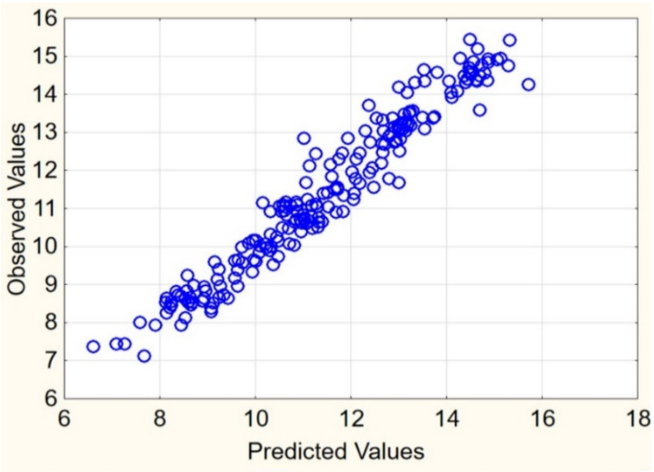

Figure 4. Comparison of predicted and observed values when justifying the average time of moving a fallen tree to the zone of its subsequent processing

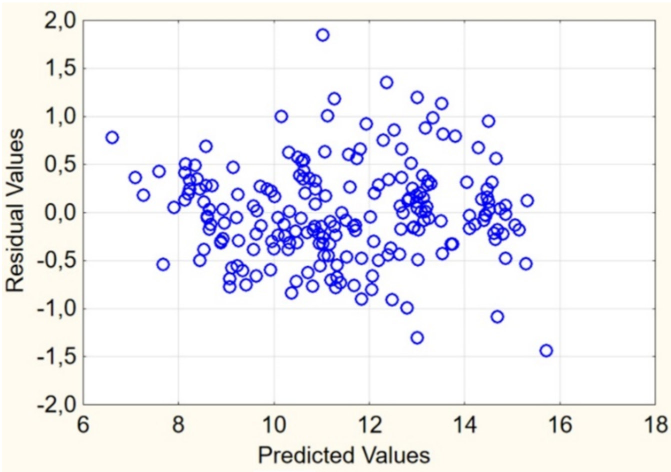

Figure 5. The graph of predicted values and residues when justifying the average time of moving a fallen tree to the zone of its subsequent processing

The volumetric graphs (Figure 6) represent a graphical demonstration of the change in the average time of movement of a fallen tree to the zone of its bucking with or without adjustment of the working position during movement in various natural conditions.

4. Discussion

The analysis of the graph in Figure 5 makes it possible to note a gradual decrease in the time of moving a fallen tree to the processing zone with an increase in the average volume of the whip in the cutting area. It can be explained by the fact that with the assumed constant value of the forest reserve per hectare, an increase in the average volume of the whip when plotting the graph corresponds to a decrease in the number of trees in the cutting area. Reducing the number of trees increases their availability for unhindered movement to the processing zone without damage to the remaining trees for rearing.

Selective logging is characterized by increased labor costs for moving fallen trees. However, when sampling less than 40% of wood by stock, there is a decrease in the average time for moving a tree despite the increase in the number of trees left for rearing (Figure 5a, b, c). This is explained by the fact that with a small proportion of the sample of the stand, the proportion of trees that felled on forwarding trails increases, and the proportion of trees harvested on swaths decreases. Logging on forwarding trails provides for 100% removal of wood from the forwarding trails, which means that trees felled on it are dragged into the processing zone unhindered, and less time is spent on their movement than when moving trees felled on swaths. As a result, the average travel time of fallen trees during partial cutting with a sample share of less than 40% is reduced. The reduction in time needed to move fallen trees with 100% removal of wood during final cutting is explained by the absence of obstacles on the way to moving them to the processing zone (Figure 5, a, b, c).

An increase in standing volume per hectare on the graphs is accompanied by an increase in the number of trees remaining for rearing, which complicates the process of moving fallen trees without damaging them and an increase in labor costs for this operation (Figure 5, b). An increase in the amount of large brushwood in the cutting area does not lead to reduction in labor costs for moving fallen trees (Figure 5, c, d). Instead, it creates significant obstacles in the process of work.

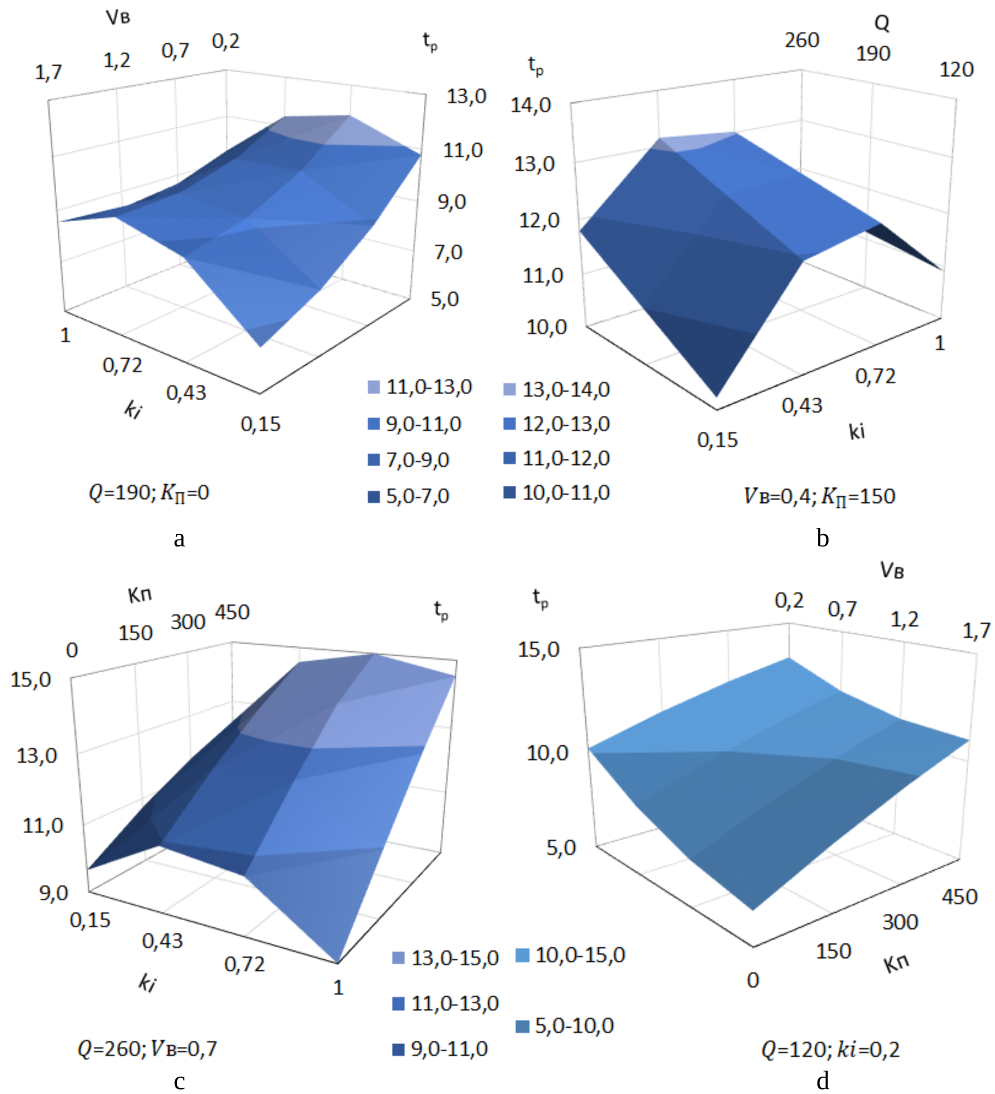

Figure 6. Graphs of changes in the average time of movement of a fallen tree to the zone of its bucking with or without adjustment of the working position during the movement

Many scientists have been engaged in modeling the technical features of harvesters and substantiating the labor norming (Mokhirev et al., 2015; Mokhirev, 2016; Kunitskaya et al., 2019; Laurila et al., 2020; Mokhirev et al., 2022). Despite the variety of existing studies, the issues of taking into account natural and production factors when working harvesters in selective logging has not been studied. Only some of results obtained during previously conducted simulation studies are presented by their developers in the form of mathematical dependencies with the possibility of their recalculation for other production conditions without the use of specialized software. Most of the existing research in this area shows that the most important role in the harvester's work cycle is played by the time felling trees, pruning branches, bucking, and moving the machine between working positions (Gerasimov et al., 2003; Rukomojnikov, 2013; Sokolov and Osipov, 2017). At the same time, the researchers focused on the mathematical analysis of the harvester's performance, and not on individual elements of its operation time.

The analysis of harvester modeling studies conducted by the authors showed that none of the existing studies aims to substantiate the relationship between the time of movement of a fallen tree to the bucking zone and the characteristics of the stand. The influence of natural conditions on the efficiency of the harvester is quite significant (Wang et al., 1998; Wang and Greene, 1999; Wang and LeDoux, 2003). The conducted research does not contradict the conclusions obtained by other scientists.

We regret that such a study has been conducted for only one technological operation and one harvester model. It is obvious that the experimental studies carried out and the results obtained will differ from the final indicators that can be obtained when working with harvesters of other models, with other technical characteristics (speed, power, machine dimensions, dimensions of the harvester head). However, this study primarily aimed to analyze the work of harvesters to assess the impact of natural factors that do not depend on the technical performance of machines. It makes it possible to assume that natural factors characterizing the quantitative indicators of the stand and the proportion of trees cut down during logging operations play an important role and will have a similar effect when using any model of machine for felling, pruning branches, and bucking trees in the cutting area. The authors agree that the cycle time element analyzed in the article is not the main one in the harvester tree processing cycle. However, this example can clearly explain one of the reasons for the decrease in output during partial cuttings.

4. Conclusion

The result of the conducted production and simulation studies, their processing and statistical analysis, and a regression model were obtained for calculating the duration of the cycle time of moving fallen trees during operation of the Silvatec 8266 TH harvester. The new calculation idea improves the possibilities of analyzing the effectiveness of the actions of operators of multifunctional cutting machines during selective logging, taking into account the complex influence of quantitative characteristics of target and non-target components of stands. The results can be used by research organizations when planning the production process of logging operations.

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