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Simulation Modeling of Labor Costs for Moving of Harvester between Working Positions in Cutting Area

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Abstract: The article discusses the technological features of the functioning of forest harvester in the implementation of logging in various natural conditions. The primary objective of this research is to ascertain the influence of trees and shrubbery on the duration of the harvester's transit between operational sites. The research was implemented by computer modeling methods based on a computer program specially created by the authors of the article to simulate the operation of a forest harvester. During the simulation, the trajectory of the manipulator from each working position of the harvester, the dimensional characteristics and location of the trees assigned to the felling and the remaining trees were evaluated. The results can be used by research organizations when planning the production process of logging operations.

Keywords: computer modeling; cutting area; felling; forest harvester; manipulator; working position

1 INTRODUCTION

When choosing machines and mechanisms for the implementation of logging operations, it is necessary to take into account a variety of factors. This is especially true when implementing selective cutting of forest, for which there is currently no general approach to labour norming. The trees remaining in the cutting area create significant obstacles to the effective work of operators of cutting machines used in felling trees. A detailed analysis of their work on the cutting area in the conditions of selective cutting of forest will allow implementing a scientific approach to labour norming for performing individual cutting operations. Focusing the attention of the readers of the article on the harvester, as a machine that is one of the most popular today by loggers around the world, we can confidently say that its performance largely depends on the average volume of tree stem and the qualifications of the machine operator. Studies of different countries conducted by Spinelli et. al. [1], McEwan [2] and Picchio et al. [3] in Southern Europe, Liski et al. [4] in Finland, Nakagawa et al. [5] in Japan, Seixas & Batista [6] in Brazil, Norihiro et al. [7], Ramantswana et al. [8], Ackerman et al. [9] in South Africa, Strandgard et al. in Australia [10] this statement is also confirmed.

Nevertheless, studies by various researchers have shown that the proportion of trees that have been cut down in relation to the overall forest composition is a significant factor in calculating the labor expenses for felling and processing trees with a harvester during selective logging [11-13]. The requirements for the safety of trees remaining for rearing during selective logging compared to continuous logging of the stand lead to the need to take into account the technological features of harvesters when creating mathematical dependencies for analyzing their performance. In this regard, the authors propose additional theoretical studies that take into account the peculiarities of the operation of these machines in the forest.

The primary objective of this research is to ascertain the influence of trees and shrubbery on the duration of the harvester's transit between operational sites.

2 MATERIALS AND METHODS

The research was conducted through the use of computer modelling techniques [14], employing a custom-designed computer program developed by the researchers to simulate the operation of a harvester in a forest environment [15-17].

The program was created in the AnyLogic simulation system. The model developed by us uses the technical characteristics of the harvester and the qualifications of the operator: the dimensions of the harvester and the harvester head, the speed characteristics of the movement of the harvester and its manipulator, the parameters of the manipulator departure, the speed of dragging the tree trunk with the harvester head and some other parameters. During the operation of the harvester, the trees of the target component are processed to ensure the safety of the trees of the non-target component. This, final felling with and without undergrowth preservation, as well as various types of thinning can be simulated.

The adjustable parameters of the stand within the designated cutting area, as specified by the investigator in the program, include the number of target component trees that must be harvested, the number of non-target component trees that should remain in place for cultivation purposes, and the number trees (undergrowth category) that may be removed during logging operations to enhance the accessibility of target component trees. The placement of all trees on the territory of the cutting area is carried out arbitrarily at each start of the simulation program. The rocks and diameters of tree trunks of all components are randomly distributed among them based on the characteristics of the breed composition and their dimensional parameters specified by the researcher.

The main limitations of the simulation model are the possibility of using it only to analyze the operation of the harvester in flat terrain, good cross-country ability, the volume of trees being processed is no more than 2 m^3, tree diameters up to 0.9 m with bucking on logs from two to six meters long.

To confirm that the results of the simulation model correspond to the real production conditions of the cutting areas, the program was tested on the basis of observations of the harvester Silvatec 8266TH [22] (Fig. 1).

Specifications:

- Engine Mercedes OM 906 LA diesel engine
- 205 kW / 278 HP at 2100 rpm
- Dynamic tractive power (theoretic): 146 kN
- 8-wheel drive
- Crane Loglift 220 V / 83 crane with 8.3 m reach
- Length: 7.70 m × Width: approx. 2.62 m with standard tyres.

Figure 1 Harvester Silvatec 8266TH

During the experiment, individual was mastered. The species composition of the stand was 100 % of pine trees. The average wood stock per hectare is 260 m^3. The average volume of trees in forest swathes analyzed during the experiments was 0.4 m^3.

The work of experienced operators with more than 5 years of experience was studied. The width of the forest swathes was 15 meters. The sections of forest swathes analyzed during the experiment had a length of 100 meters. In the course of experimental studies, 9 different forest swathes were developed with a different number of trees (k_D) on them and a different proportion of trees being cut down (k_i).

In the process of production experiments, a Latin square experiment plan was used with varying factors at three levels n = 3, having the form shown in Tab. 1. This plan allowed for uniform scanning of the factor space and confirmed the significance of the factor features used in the experiment (k_D), (k_i).

Table 1 Representation of the Latin square taking into account the levels of variable factors of the production experiment

The proportion of trees being cut down (k_i)	Number of trees per 1 ha (k_D), pcs.		
	k_{D1} = 200	k_{D2} = 400	k_{D3} = 600
k_{i1} = 0,2	P_{h1}, t_{nav1}, t_{pod1}, t_{per1}	P_{h4}, t_{nav4}, t_{pod4}, t_{per4}	P_{h7}, t_{nav7}, t_{pod7}, t_{per7}
k_{i2} = 0,6	P_{h2}, t_{nav2}, t_{pod2}, t_{per2}	P_{h5}, t_{nav5}, t_{pod5}, t_{per5}	P_{h8}, t_{nav8}, t_{pod8}, t_{per8}
k_{i3} = 1,0	P_{h3}, t_{nav3}, t_{pod3}, t_{per3}	P_{h6}, t_{nav6}, t_{pod6}, t_{per6}	P_{h9}, t_{nav9}, t_{pod9}, t_{per9}

During the trial, the hourly productivity of the harvester was logged for each forest strip (P_h). The duration of the manipulator's pointing action (t_{nav}), and the time it took to drag the tree to the processing area (t_{pod}), were also recorded. Furthermore, the time required to move the harvester between workstations for each tree (t_{per}) was measured.

The results of the production experiment were compared with the results of simulation modeling. The final comparison of the obtained numerical values showed good convergence of the results. The discrepancy between theoretical and experimental values did not exceed 12% for all analyzed indicators. The obtained conclusions confirmed the adequacy of the model to real production conditions. After the experiment, an additional adjustment of the simulation model was carried out. The identified inaccuracies of its operation were taken into account. This made it possible to further increase the convergence of the results obtained.

For a clearer understanding of the reasons for the reduction of labor costs during the operation of the harvester on final felling and their increase during thinning, a comparative analysis of the movements of the harvester was carried out. The analysis allowed us to identify a number of distinctive features associated with the movements of the harvester. In particular, it was noted that during selective logging in order to ensure the safety of the quality of the trees remaining for rearing, in order to avoid defects in the trunks that violate the integrity of the wood, such as bark peeling, bullying, scratches, dents, etc. The following technological features are observed in the operation of the harvester:

- if there are obstacles in the form of non-target component trees, the path of the manipulator to the tree that is planned to be cut down becomes longer;
- when transferring a fallen tree to a processing area, it may be necessary to adjust the position of the harvesting machine in order to avoid causing damage to other trees. This may require the machine to move in the opposite direction;
- the total distance traveled by the harvester between the trees increases due to the displacement of the harvester back in the process of adjusting working positions.
- with a small proportion of the failed component in the composition of the stand, the frequency of changing working positions increases due to the low availability of trees of the target component.

Further simulation was carried out on the basis of the results of real production data collected during the production experiment.

For the computer-based experiment, a factorial design with four factors was developed, with each factor varying at four levels, resulting in a 4×4×4×4 factorial design. The experiment was implemented with a complete search of options. Among the main variable factor features were used: timber volume per hectare (Q), m^3/ha; the amount of large undergrowth per hectare K_p, pcs/ha; the average volume of tree stem (V), m^3

Variation of parameters was carried out in the ranges presented in Tab. 2.

Table 2 Range of variation of factor features during the implementation of simulation modeling of harvester operation

Symbol	Variation levels			
	1	2	3	4
Q	50	120	190	260
k_i	0,2	0,4	0,6	1
K_p	0	150	300	450
V	0,2	0,7	1,2	1,7

In the course of simulation modelling, the influence of the enumerated factors on a specific component of the harvester cycle time was evaluated. This element was defined as the average time taken by the harvester to move between working positions while feeling a single tree (t_{per}), sec.

3 RESULTS

As a result of the simulation, a regression model (1) was created to predict the average time it takes for the harvester to move between working positions during selective logging:

$$t_{per} = \frac{\left[d_0 + k_i(d_1 + d_3Q + d_5K_p) + K_p(d_2 + d_4Q)\right]}{Qk_iV^{d_6}}. \qquad (1)$$

The results of calculating the coefficients of the regression equation and their confidence intervals are shown in Tab. 3. The results of the table 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 coefficients of the regression equation. 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.

Table 3 Conducting statistical analysis of the significance of the regression coefficients per tree

	Estimate	Std. Err	t-test	P-value	–95% CL	+95% CL
d_0	1474,823	13,849	106,495	0,0000	1447,512	1502,134
d_1	–305,263	40,764	–7,489	0,0000	–385,652	–224,873
d_2	–0,28227	0,06518	–4,33041	0,0000	–0,411	–0,154
d_3	0,937587	0,248288	3,776211	0,0002	0,448	1,427
d_4	0,001719	0,000332	5,183645	0,0000	0,001	0,002
d_5	0,864121	0,129283	6,683950	0,0000	0,609	1,119
d_6	–0,893	0,007	–126,354	0,0000	–0,907	–0,879

Statistical processing of the results at the level of significance of 0,05 according to the Kohren criterion proved the possibility of reproducibility of the obtained values. The computed value of the Coherent coefficient invalidating the mean time of the harvester's movement between operational sites per tree was G_p = 0,007. This value did not exceed the critical table value of the Kohren coefficient equal G_{kp} = 0,011. The ratio $G_p < G_{kp}$ made it possible to conclude that the variances are homogeneous.

The multiple coefficient of determination R^2 of the nonlinear model was 0,896 (Fig. 2). This value serves as an indication that the alteration in the meantime taken by the harvester to move between harvesting positions for each tree is contingent upon variations in the variables incorporated into the regression model. This dependence is not accidental.

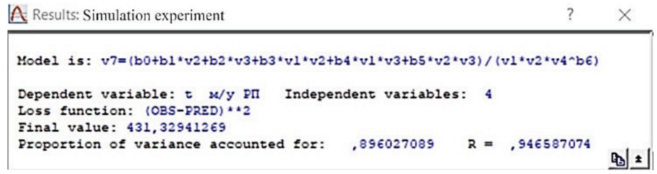

Figure 2 Results of building regression model

The calculated value of the significance level is less than the set value of 0.05. Therefore, the calculated indicators of statistical processing of the average time of moving of the harvester between working positions per tree, presented in Tab. 4, indicate the significance of the coefficient of determination.

Table 4 Analysis of variance

	Sum of Squares	df	Mean Squares	F-value	p-value
Regression	265067	7,0000	37866,8	17294,8	0,00
Residual	431,3	197,00	2,19		
Total	265499	204,000			

The construction of a normal probabilistic graph (Fig. 3) allowed us to conclude that there were no systematic deviations of the results of regression modeling from the theoretical normal line. All points (residuals) on the graph are close to the line expected for normally distributed residuals.

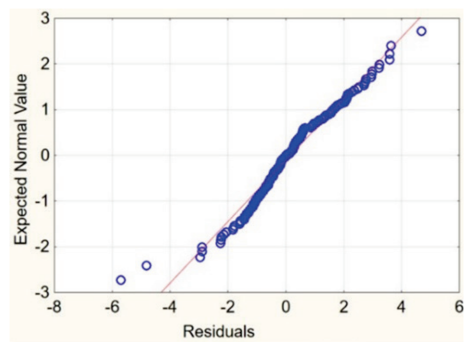

Figure 3 Normal probabilistic graph

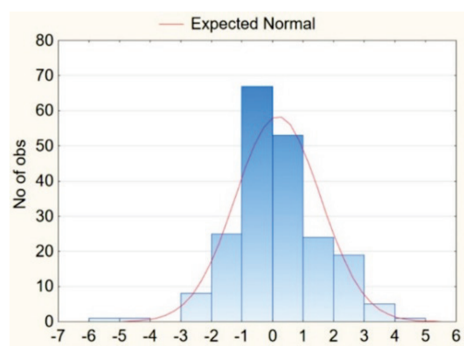

Figure 4 Histogram of residue

The histogram of the data presented in Fig. 4 also serves as a visual confirmation of the proximity of the distribution of harvester movement times between harvesting positions per tree to a normal law distribution.

In Fig. 5 presents comparative analysis of the predicted and observed values. In Fig. 6 shows graph of the predicted values and residues. Analysis of the graphs allows you to note only a slight discrepancy between the results recorded on the simulation and regression models. Graphs make it possible to declare the adequacy of the regression equation with the results of computer simulations.

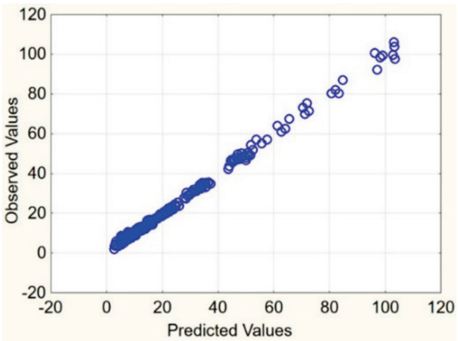

Figure 5 Comparison of predicted and observed values

The picture shows how the change in the average time it takes for the harvester to move between trees changes in different natural conditions is presented on three-dimensional graphs (Fig. 7).

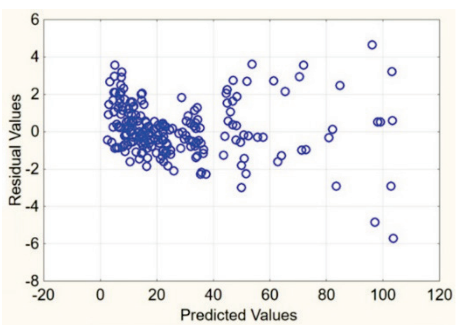

Figure 6 Graph of predicted values and residues

The analysis of the data presented in Fig. 7 reveals a steady growth in the time required for the harvester to moving between harvesting positions for each individual tree as the average volume of the tree stem increases and the same average wood reserves per hectare (with a decrease in the number of trees in the cutting area). However, this increase in time has the most significant impact on the operating time of the machine, only with selective cutting in cutting areas with less than 40 percent of the timber volume being cut down (Fig. 7a).

The main factor that affects the analyzed element of the harvester's cycle time is the proportion of non-target tree components during cutting (Fig. 7b, 7c, 7d). This is because a reduction in the number of trees being cut results in a longer total travel time for the harvester in the cutting area, when calculated per tree.

The quantitative indicators of undergrowth within the cutting area have an impact on the average time taken by the machine to move between working positions for each individual tree. This occurs only when the proportion of cutting trees decreases and the dimensional specifications of the trees designated for felling increase, with a constant average supply of wood per hectare (Fig. 7c, 7d). In such cases, due to an increase in the quantitative indicators of the undergrowth at the cutting, the increase in labor costs can reach 50% of the minimum recorded in the construction of the graphs of the analysis results.

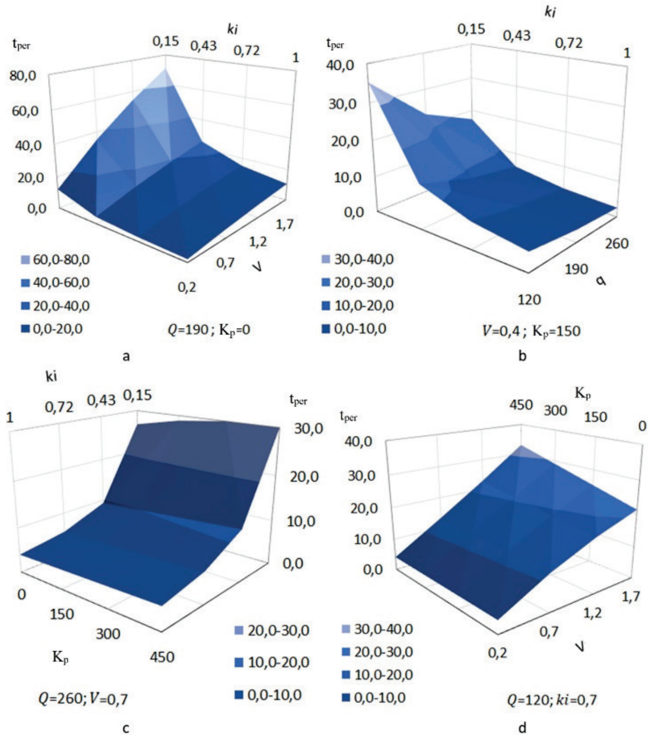

Figure 7 The diagrams depict the fluctuations in the mean travel time of the harvester between harvesting positions per tree

4 DISCUSSION

Substantiation of the effectiveness of the use of logging machines is an important and responsible task facing the owner of any logging and forestry enterprise. The impact of natural and climatic factors on the efficacy of operations within the timber extraction sector is substantial. So, the correct selection of logging machines is currently of great importance [19]. Of particular relevance is the imitation of technological processes of logging operations when analyzing the tasks of using modern multioperative equipment. In most cases, standards for calculating efficiency and labor rationing have not yet been developed for this equipment when planning the activities of enterprises in changing environmental conditions [20, 21]. The introduction of forest harvesters in the technological process of logging operations sets itself a wide range of tasks to improve the efficiency of their use [22, 23]. According to many prominent scholars, the processes of managerial and organisational decision-making, as well as the establishment of labour standards and the development of regulatory documentation, can and should be automated. This should be done based on the specific type of logging operation, the qualitative and quantitative features of the cutting area, and the technical specifications of the equipment employed, with utmost regard for random natural and operational variables [24, 25].

A critical examination of the existing body of research in this field reveals that the studies conducted by other scholars frequently employ simulation modelling to investigate the functioning of forest harvesters [26-28]. The simulation models developed by them, provided that the researcher has access to the appropriate software, can be executed repeatedly to analyse the performance of the harvester under various environmental conditions. They make it possible to mathematically substantiate various parameters of the harvester's operation technology. But in order to use these software developments, it is necessary for developers to provide open access to the use of their simulation models. In addition, when using each specific simulation model, it is necessary to train users to achieve research results. All this makes it advisable for developers to create of various mathematical dependencies based on the results of multiple experiments on their models. Obtaining mathematical dependencies is a rational result of analyzing the operation of machines in the process of simulation modeling of a number of scientists from different countries. The developers of existing models focus readers' attention primarily on finding such important elements of the harvester's work as productivity and cycle time with a diverse combination of natural and industrial factors [29, 30] A number of scholars set forth more intricate objectives and dissect the overall duration of processing a single tree into distinct components of the processing cycle time. Most scientists divide the time it takes to process a tree trunk into 5 or 7 main parts [31, 32]. Some of them depend only on the parameters of the trees being processed and the technical characteristics of the harvester. They can be described by mathematical dependencies that do not require a simulation process. These include mathematical dependencies for determining the time of cutting down a tree, bucking the trunk, and dragging the trunk through the knives of the harvester head [33, 34]. But there are other elements of the cycle time that depend not only on the characteristics of the machine, but also on the relative position of the trees in the forest. Such indicators are random variables and multiple experiments are necessary to determine them. Specifically, the analysis has led to the conclusion that at present, there are no mathematically derived relationships available for determining the average time taken by a harvester to move between harvesting positions for harvesting a tree in diverse natural settings.

The data clearly indicates a rise in the average time required for the harvester to move to each new position, coupled with a reduction in the number of trees felled within a given area and an expansion of the distance between individual trees. However, during the experiment it was noted that during selective logging, the harvester operator in some cases has to simultaneously move the harvester along the fiber in the opposite direction with the movement of the manipulator. This is done in order to minimize damage to the remaining trees when they are moved to the processing area. Moving the harvester in the opposite direction subsequently increases the distance traveled by the harvester when moving forward to the next working position and, in general, the total distances of the harvester's movements along the cutting area. This demonstrates that not only does the quantity of trees that are felled affect the average time required for a harvester to move between work sites, but also does the number of remaining trees remaining for rearing.

Existing models cannot be applied to find this indicator. As a result, many researchers recommend only a certain range of values for this indicator, regardless of the type of logging and working conditions in the forest [31-35]. This significantly reduces the accuracy of calculations when justifying the desired parameters. Furthermore, the dearth of theoretical data necessary to verify the metric of the mean time spent by a harvester traversing between operational positions during various types of logging operations precludes the analysis of the impact of external technical and technological variables on this metric across a spectrum of the stand thinning intensities.

5 CONCLUSION

Thus, according to the authors of the article, this study improves the current state of knowledge in comparison with existing studies. The presented mathematical relationship presented herein is novel, enabling us to accurately and convincingly account for the variation in the time taken for a harvester to move between work positions in diverse configurations of factors at a logging site. It has practical significance for the forestry industry. The introduction of novel mathematical correlations elucidating the impact of extrinsic variables on the performance of a harvesting machine will enhance the efficacy of devising logging techniques and scrutinizing their ultimate operational metrics. The results can be used by research organizations in planning the production process of logging operations.

Acknowledgments

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