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SIMULATION MODELING OF LOGGING HARVESTER MOVEMENTS DURING SELECTIVE LOGGING

Konstantin Rukomojnikov*, Tatiana Sergeeva

Volga State University of Technology, Yoshkar-Ola, Russia

** rukomojnikovkp@volgatech.net*

The purpose of this research is to substantiate the mathematical regularities of the harvester operation, allowing for rapid technical calculations of labor costs with a sufficient level of reliability when performing various logging operations. The article describes the simulation model of harvester movement in the cutting area, created by the authors to analyze the operation of the harvester at various logging sites. Examples of visualization of the program and the results obtained with its use are given. Four-factor experimental plan was drawn up with varying factors at four levels. The results obtained during the simulation have been statistically processed. The analyzed elements of the cycle time are: the average time of pointing the manipulator at a tree, the average time of moving a fallen tree to the processing zone and the average time of moving the harvester between working positions per felled tree. The regression dependencies obtained as a result of the analysis are based on four indicators. Such indicators are: the total stock of wood per hectare, the share of the felled component of the stand, the amount of undergrowth (rowan, bird cherry, willow, etc.) in the cutting area, the average volume of the tree in the cutting area. The found patterns give the researcher a general idea of the effectiveness of the equipment in specific natural conditions of cutting areas. The use of the acquired knowledge in the analysis of harvester performance will improve the accuracy of planning the work of logging crews.

Keywords: regression dependence, cut-to-length harvesting, labor costs, cutting area

1 INTRODUCTION

Harvester+ forwarder systems have been used for many years in the Scandinavian countries [1-4]. Almost 100% of today's harvesting in Sweden and Finland is carried out by systems for cut-to-length harvesting [5, 6]. Various researches have been conducted in these and other countries, including productivity analysis [7-10] and harvester assessment in the wood supply chain [11-13]. In North America, systems for cut-to-length harvesting are used in about 20-30% of cases [14]. Even fewer are used in the southeastern United States, where no more than 1% of its use has been recorded [15]. In Russia, the share of cut-to-length logging in the total volume of logging is approximately 30%, and in the North-West it reaches 90%, which is due to the proximity of Finland and the small size of the forest cuttings [16, 17].

It is difficult to assess the impact of all natural and production factors in real production conditions due to the need to conduct a significant number of experimental studies in order to achieve reliable results [18-20]. Therefore, when searching for rational production options in order to increase the economic, technical and technological efficiency of the enterprise, in many cases it is preferable to use simulation modeling [21] as one of the classes of mathematical modeling.

The purpose of this researches is to substantiate the mathematical regularities of the harvester, which allow with a sufficient level of reliability to carry out rapid technical calculations of productivity and labor costs when performing various logging.

2 MATERIALS AND METHODS

The main method for the implementation of simulation modeling was chosen the method of agent-based modeling of processes [22].

To simulate the work of a forest harvester in the Anylogic software environment [23], the authors of this article created a simulation model of the harvester movement along the forest cutting area [24-27].

Fig. 1. An example of running a forest harvester simulation program in the Anylogic software environment

An example of visualization of the movement of a forest harvester through a forest cutting area in the process of launching the proposed simulation model in the Anylogic software environment is shown in Fig. 1. At the first stage, the location of the main modeling agents is randomly simulated on the user-selected forest cutting, which are the trees cut down on the cutting, the trees remaining on the cutting, the undergrowth (rowan, bird cherry, willow, etc.), and the initial location of the harvester on the loading line is determined. At the same time, the qualitative, volumetric and dimensional characteristics of trees and undergrowth are randomly distributed based on the initial data entered by the user.

During the launch of the proposed simulation program, a simulation of sequential felling of trees and movement of the harvester from one working position to another is carried out, taking into account technical, technological and organizational breaks.

During the entire time of operation of the simulation model, the model time is taken into account, the analysis of volumetric and qualitative characteristics, harvested wood is carried out, followed by the justification of the hourly or shift productivity identified during the simulation.

One of the elements of the scientific novelty of the proposed model is the consideration of a number of recommendations in the training of operators of logging machines. These recommendations divide the area of operation of the manipulator into several main sectors [28,29]. They take into account the sequence of development of each of these sectors and the technological features of felling trees in each of them. This distinguishes the proposed approach to modeling from the principle of sequential felling of trees closest to the machine, embedded in previously known systems of simulation modeling of logging operations. The sequence of felling trees plays an important role in the study, since the removal of a part of the trees gradually reduces the number of obstacles to felling the next trees. This makes it possible to evaluate not only the technological features of the development of the cutting area as a whole, but also to detail research on the analysis of alternative work options within each working position.

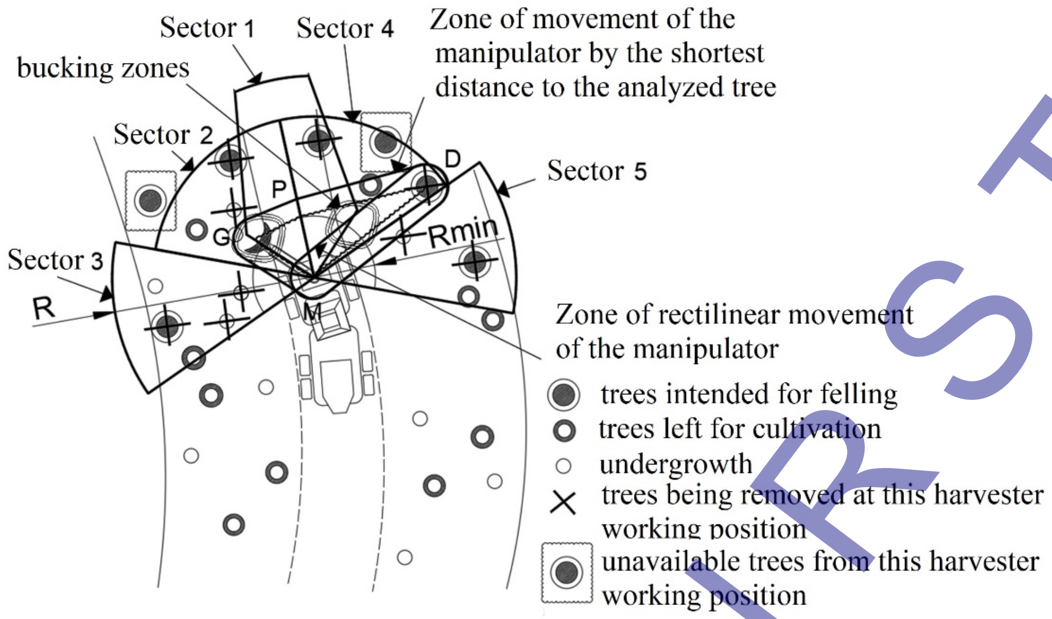

Fig. 2. Scheme of division of the site processed by the harvester into sequential processing sectors

The scheme of dividing the site processed by the harvester into sectors laid down in the simulation model is presented in Fig. 2.

The created model provides for work in each sector in the following sequence:

- Felling of all trees in the first sector with clearing of forwarding trail and thinning of the borders of the forwarding trail in the zones of subsequent cutting of fallen trees into logs;
- Thinning of the second and then the third sector with the movement of fallen trees to the cutting zone located to the right of the harvester in the opposite side of the drag from the developed sectors;
- Sequential thinning of trees in the fourth and fifth sectors with the laying of logs in the cutting zone to the right of the harvester.

One of the distinctive characteristics of the research carried out during the simulation is the analysis of the choice of the trajectory of the manipulator in the implementation of selective cuttings. It is based on the analysis of the zone of movement of the manipulator by the shortest distance to the analyzed tree. If the program detects the presence of any trees in this zone, then they represent obstacles to the free movement of the harvester head and the decision is made about the impossibility of moving the harvester head along the shortest distance to the tree. In this case, the need to analyze the possibility of a two-stage movement of the manipulator is revealed. The first stage involves turning the manipulator along the smallest possible turning radius from its original position to the zone of further rectilinear movement to bypass obstacles. The second stage involves the analysis of the presence of obstacles in the zone of rectilinear movement of the manipulator. In this case, several options are possible:

- In the considered zone of rectilinear motion there are trees of a non-target component. In this case, the tree being analyzed for capture is recognized as inaccessible from this working position and the other nearest tree in the same sector is selected. If no other tree is found, the next sector is analyzed in the selection sequence described earlier;
- There are obstacles in the form of undergrowth in the considered rectilinear movement zone. In this case, the tree being analyzed for capture is recognized as available, but the obstacle identified in the path of the manipulator movement is subject to felling and fragmenting;
- There are no obstacles in the form of any trees in the considered zone of rectilinear movement. In this case, a rectilinear movement of the harvester head to the felled tree is carried out.

The third stage is carried out after felling of the tree, in the wake of the capture and cutting, and provides for its movement to the bucking zone, located in the opposite side of the forwarding trail from the developed sector. In this case, several options are possible:

- In the zone of rectilinear movement of the manipulator along the trajectory along the axis of the fallen tree, there are no obstacles to the movement of the manipulator. In this case, the movement of the fallen tree to the bucking zone is carried out along the shortest trajectory;
- The movement of the fallen tree along its axis from the felling site to the bucking zone along a rectilinear trajectory is impossible due to the presence of obstacles in the form of other trees in the zone of movement of the manipulator along the shortest distance. In this case, it is necessary to adjust the working position of the harvester to ensure the movement of the fallen tree without damaging the growing trees.

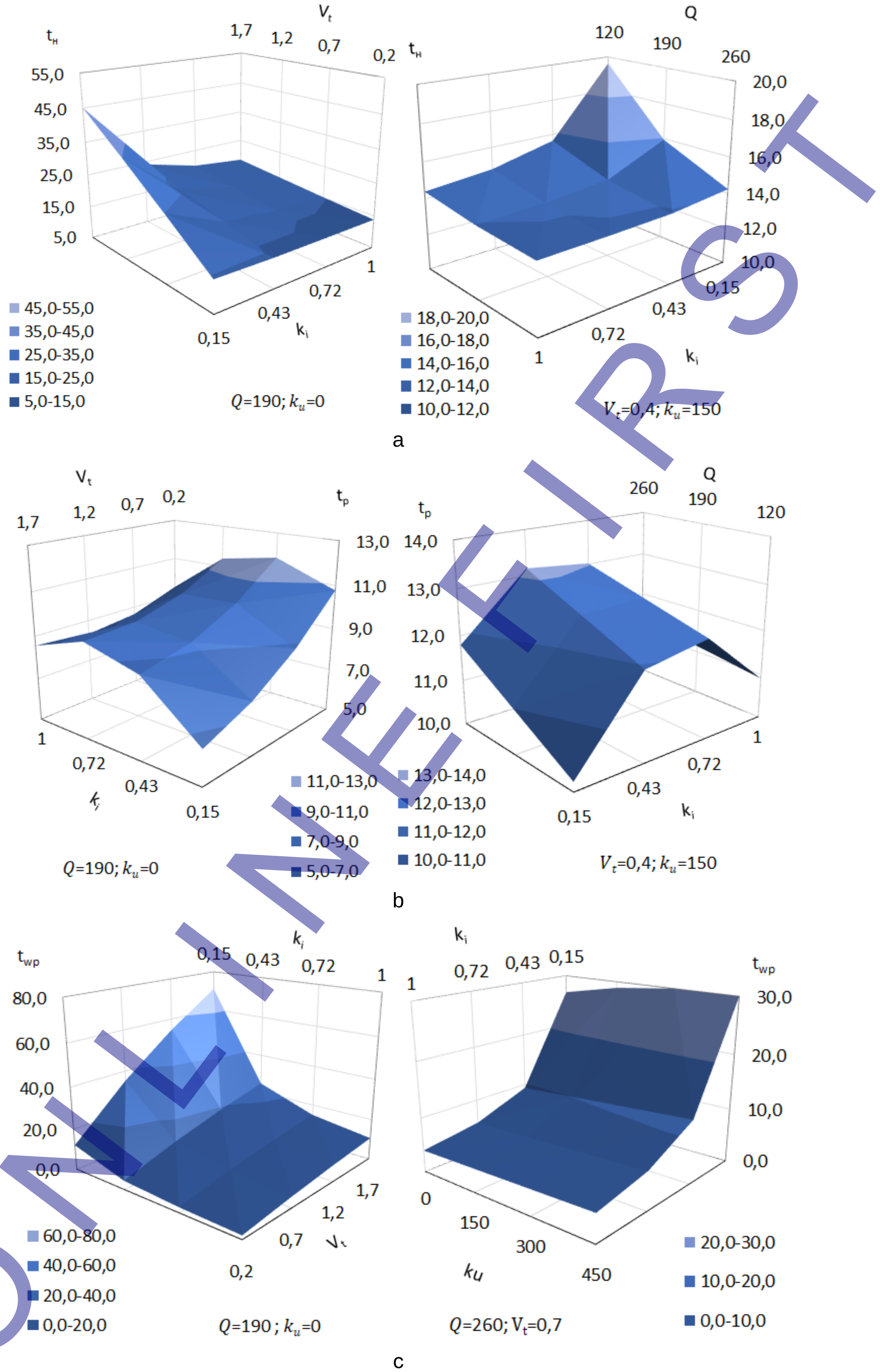

Fig. 3. Graphs of changes in the time elements of the harvester movements

a) Graphs of changes in the average time of analysis of the availability of tree, removal of obstacles and pointing manipulator in various natural conditions of cutting areas; b) Graphs of changes in the average time of movement of a fallen tree to the zone of its subsequent processing; c) Graphs of changes in the average travel time of the harvester between working positions per felled tree.

The collection of statistical data on the average speed characteristics of the harvester movement, rotation and rectilinear movement of its manipulator was carried out while observing the operation of the harvester Silvatec 8266TH. After that, it was decided to conduct experimental studies on a simulation model to analyze the influence of forestry factors on individual elements of the harvester's cycle time.

Variation of forestry factors was carried out in the ranges presented in Table 1.

Table 1. Range of variation of factor features during the implementation of simulation modeling of harvester operation

Index	Symbol	Variation levels			
		1	2	3	4
Total standing volume of wood per hectare, m3/ha	Q	50	120	190	260
Removal intensity of standing volume	k_i	0,2	0,4	0,6	1
Amount of understory per hectare, pcs/ha	k_u	0	150	300	450
Piece volume of the component to be cut, m3	V_t	0,2	0,7	1,2	1,7

3 RESULTS

The results obtained in the course of simulation modeling were statistically processed [11, 29].

The use as an effective indicator of the average time of the Silvatec 8266 TH operator's analysis of the availability of felled tree, the removal of obstacles in the form of a large undergrowth and pointing the manipulator at the tree allowed us to obtain the following regression dependence:

$$t_H = \frac{\begin{pmatrix} -16{,}8924+Q\cdot(13{,}6398\cdot k_i-0{,}6323)+ \\ +k_u\cdot(0{,}150539-0{,}17207\cdot k_i)+ \\ +V_t\cdot(42{,}82234+1{,}32378\cdot k_u)- \\ -0{,}00019\cdot k_u^2-18{,}4956\cdot V_t^2 \end{pmatrix}}{Q\cdot k_i\cdot V_t^{0.0021955}} \quad (1)$$

The multiple coefficients of determination R^2 was 0.892.

The use as an effective indicator of the average time of moving a fallen tree to the zone of its subsequent processing with and without adjusting the working position during the movement allowed us to obtain the following regression dependence:

$$t_p = 7{,}56 + Q\cdot(0{,}015856 - 0{,}00942\cdot k_i - 0{,}00001\cdot k_u - 0{,}00407\cdot V_t) + +k_i\cdot(10{,}5997 + 2{,}572018\cdot V_t) + k_u\cdot(0{,}00794\cdot k_i + 0{,}007483) + +V_t\cdot(0{,}002222\cdot k_u - 4{,}3837) - 9{,}45\cdot k_i^2 - 0{,}000004\cdot k_u^2 + 1{,}045626\cdot V_t^2 \quad (2)$$

The multiple coefficients of determination R^2 was 0.845.

The use of the average harvester travel time between working positions per felled tree as an effective indicator allowed us to obtain the following regression dependence:

$$t_{wp} = \frac{\begin{pmatrix} k_i\cdot(0{,}937587\cdot Q-305{,}263+0{,}864121\cdot k_u)+ \\ +k_u\cdot(0{,}001719\cdot Q-0{,}28227)+1474{,}823 \end{pmatrix}}{Q\cdot k_i\cdot V_t^{-0{,}893}} \quad (3)$$

The multiple coefficients of determination R^2 was 0.896.

Graphical demonstration of the changes in the time elements of the harvester movements is shown on Fig. 3.

4 DISCUSSION

According to many leading researchers, the solution of issues of making managerial and organizational decisions of labor norming and preparation of regulatory documentation can and should be computerized depending on the type of felling, the qualitative and quantitative characteristics of the merchantable volume, the technical characteristics of the equipment used with the maximum consideration of random natural and production factors [32-35]. A lot of research has been carried out by computer modeling of logging operations using a harvester [36-39].

The novelty of the approach proposed in the article includes the fact that, unlike many previously created systems of discrete-event simulation of forest development processes [40-46], the main method for the implementation of the project was chosen the method of agent-based simulation of these processes. This method allows analyzing the actions of decentralized dynamically interacting agents and simulating production processes, moving from micro-level indicators to macro-level indicators.

All existing research in this area shows that the most important role in the harvester cycle is played by the time of felling, limbing, cutting and moving the machine between working positions [47-49]. At the same time, the influence of natural conditions on the efficiency of the harvester is quite large [50]. However, the authors' analysis of studies of modeling the work of harvesters showed that none of the existing studies aims to substantiate the dependence of the time and movements of the harvester between trees, the movements of its manipulator when capturing the trunk and the movements of a fallen tree from the characteristics of the merchantable volume. The main objective of our study is to show how natural factors affect individual elements of the cycle time.

The analysis of existing mathematical dependencies demonstrates the possibility of taking into account the influence of the share of the cut component k_i using simpler mathematical dependencies [51-55]. However, it can be noted that the mathematical dependencies proposed by other authors do not focus the attention of researchers on reducing the availability of trees due to obstacles created by trees remaining in apiaries and undergrowth. In addition, none of the described existing studies analyzes the increase in labor costs during harvester operation in the presence of large undergrowth on the cutting area, creating obstacles, but not taken into account in the total volume of harvested wood.

An attempt to use these previously known mathematical dependencies to substantiate the numerical results of simulation modeling showed low coefficients of determination of these equations in the natural production conditions selected during modeling.

The authors agree that the elements of the cycle time analyzed in the article are not the main elements in the harvester tree processing cycle, but they believe that this example can clearly explain one of the reasons for the decrease in output during intermittent logging.

5 CONCLUSIONS

Regression models have been obtained that allow the researcher to analyze the efficiency of the harvester in a wide range of variation of natural factors.

The main indicators that affect the productivity of the harvester are the average volume of tree in the cutting areas and removal intensity of standing volume. However, labor norming is impossible without taking into account the influence of such natural factors as the total standing volume per hectare and the amount of large understory in the cutting area. In contrast to the average volume of tree on the cutting area, the impact of which on productivity is obvious with any degree of thinning of the stand, the influence of these factors is most pronounced in the implementation of selective logging, which leads to the need for a more thorough analysis of the factor characteristics of the stand when labor norming during their implementation compared to clear-cutting. The most tangible influence of the noted factors is recorded when the removal intensity of standing volume decreases below 40% and increases as this value decreases.

The use of these regression models for other cut-to-length harvesting machines contributes to the approximate calculation of the desired values and gives the researcher a general idea of the efficiency of the equipment in specific natural conditions of the forest cutting, which in many cases is sufficient for practical purposes forestry and logging enterprises.

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