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Simulation modelling of the felling-bunching machine logging operation with the multiple-tree accumulating head

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Abstract. This study deal with the productivity of felling-bunching machine for differently aged forest when using conventional logging heads (CH) and multiple-tree accumulating head (AH). Experimental studies of logging technological processes using AH and CH-based felling-bunching machine were carries out for harvesting of large-sized and thin tree. We used total number of thin and large-sized trees in the working zone, 6…10 and 1…5 trees, respectively, and the average volume of thin and large-sized tree stick, 0.0042…0.096 and 0.26…2.26 m^3, respectively, as independent variables. It is shown that the felling-bunching machine productivity per shift increases with the number of trees within the working zone. At the same time, with increase of total number of trees within the working zone, the productivity decreases. The highest productivity of the machine is in the harvesting only large-sized trees. In practice, it is possible to recommend joint harvesting of large-sized and thin trees, when the average volume of the large-sized tree stick does not exceed the two volumes of thin trees.

1. Introduction

Modern industrial logging, based on harvester+forwarder or felling-bunching machine (FBM)+skidder systems achieves the highest productivity in forests with mature trees of the same size and quality. Such forests, where were carried out thinning operations, for example, are in Scandinavian countries [1]. As for the forests of Russia, often thinning operations are not carried out. This is one of the reasons why the trees in these forests are of different ages.

The number of large-sized trees in differently aged forest does not exceed 50%, and the number of small trees can be more than 50%. In practice, the productivity of logging machines on the harvesting of thin trees by conventional logging heads (CH) is significantly reduced.

Today, thin trees [2-4] and logging residues [5-7] are in demand and are widely used in bioenergy in the form of fuel chips [8-9]. Harvesting of thin trees together with large-sized trees faces a number of difficulties. For example, the cycle time for harvesting the large-sized and thin trees is almost the same. However, when the tree diameter of 32 cm at chest level, its volume will be 0.8 m^3, and when the tree diameter of 8 cm … 0.03 m^3.

The challenge of logging operations in differently aged forest commonly met in central and southern Europe is to find efficient harvesting tools and technologies for harvesting large-sized and thin trees together [10-12]. The efficiency of the machines in harvesting of thin trees can be significantly improved by using multiple-tree accumulating head (AH), where trees with diameter of less than 12-14 cm are cut, gripped and accumulated in the AH. The volume of thin trees in the AH is about equal to the volume of large-sized tree. This technology considerably reduces the cycle time, which makes harvesting of thin trees on the effectiveness comparable to the harvesting of large trees.

Today, harvesting of thin trees is carried out by the FBM usually with the help of the AH (figure 1). In this work, the FBM moves along a track from one working stop to another. Then from each stop, it cuts thin trees within reach of the manipulator, accumulating them in the AH. Then the accumulated packs of trees are laid along to the track on the cutting area (figure 2).

The aim of this paper is to estimate the productivity of the FBM in the differently aged forests using combination of CH and AH technologies.

Figure 1. Harvesting thin trees with the help of the multiple-tree accumulating head (photo by the author).

Figure 2. A pack of thin trees on the cutting area after harvesting by the multiple-tree accumulating head from one working stop (photo by the author).

2. Materials and methods

We considered tree harvesting in the forest of different ages by FBM with the AH. The FBM used the combination of CH and AH technologies. The FBM moved through the cutting area from one working stop to another. On each working stop, the FBM cut off trees and stacked them in the pack.

In these operations, the FBM used AH in two modes: as AH or CH.

In this paper, we considered three cases of the FBM working: the first case of harvesting only large-sized trees in CH mode, thin trees ignoring; second case of harvesting large-sized trees in CH mode and thin trees in AH mode, and the third case (harvesting large-sized trees in CH mode and thin trees in CH mode.

The intensity of FBM harvesting (λ_{FB}) was determined by the formula:

$$\lambda_{FB} = \frac{1}{T_{c.FB}} \tag{1}$$

where $T_{c.FB}$ was the FBM cycle time needed for processing trees, sec.

The hourly productivity (P_{hour}) of the FBM on the logging operation was determined by the following formula:

$$P_{hour} = \frac{3600 \cdot q \cdot n_{\max}}{T_{c.FB}} \tag{2}$$

where q – average volume of tree stick (for CH mode) or pack of trees (AH mode), m^3; n_{max}– maximum number of trees in the AH.

The shift productivity (P_{shift}) of the FBM on the logging operation was determined by formulas follows:

$$P_{shift} = P_{hour} \cdot (T - t_p) \cdot k_1 \cdot k_2 \tag{3}$$

where T– duration of the shift, sec.; t_p – regulated down time, sec.; k_1–coefficient of equipment use, k_1 = 0.8 ... 0.9;k_2 – coefficient of working time, k_2 = 0.8 ... 0.9.

Maximum number of trees in the AH for different operation modes: in the CH mode $n_{\max}$ was 1 and in the AH mode $-n_{\max} = k \cdot S_{\max} / S$, where S_{max} – maximum capture area of the AH, m^2; S – area of the tree section, m^2; k – coefficient of density of the tree pack in the AH.

The maximum number of trees that was captured and hold by the AH depending on tree diameters. In our study, the number of thin trees inside the working zone of the FBM, did not exceed 5 trees.

The cycle time of the cutting and laying the tree in a pack by the FBM in the CH mode ($T_{c.FB.CH}$) was determined by the following eqaution:

$$T_{c.FB.CH} = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7 \tag{4}$$

where t_1 – time to direct (supply) of the cutting head to the tree, sec.; t_2 – time to grip and pull the tree trunk up, sec.; t_3 – time of pushing (removal) of a tree from a stump, sec.; t_4 – time to lift the trunk and reduce the departure of the manipulator, sec.; t_5 – time to turn the platform of the FBM, sec.; t_6 – time to tilt of the cutting head and stacking tree in the pack, sec.; t_7 – time to turn the platform of the FBM, sec.

The cycle time of the cutting and laying the tree in a pack by the FBM in the AH mode ($T_{c.FB.AH}$) is determined by the formula:

$$T_{c.FB.AH} = \frac{\left[(t_1 + t_2 + t_3) \cdot n_{\partial} + t_4 + t_5 + t_6 + t_7\right]}{n} = \frac{t_4 + t_5 + t_6 + t_7}{n} + (t_1 + t_2 + t_3) \tag{5}$$

where n – number of thin trees in the AH.

The number of trees in the working zone and their diameter was random and depended, in particular, on the stock of wood. In our studies, the characteristics of trees in the working zone were taken as independent factors and determined by mean values. The number of factors and their values are given in the table 1.

The time cycles of the work of the FBM in different modes of the AH will be random numbers. In this work, for the cycle time, an exponential distribution law with an average value depending on the mode of operation of the AH related to one tree is adopted.

Research of these technologies was carried out by methods of computer simulation [15-18].

Table 1. Independent variables and their variation levels.

Factors	min level	max level
Number of trees in the working zone, trees.	6	10
Number of thin trees in the working zone, trees	1	5
The average volume of large-sized tree stick, m^3	0.26	2.26
The average volume of thin tree stick, m^3	0.0042	0.096

3. Results and discussion

In experiments with the simulation models, four factors were adopted (table 1). The impact of each factor on the productivity of the FBM working in operating mode AH has been established via analysis of variance of data modeling.The results of the analysis of variance are given in the table 2.

Table 2. Dispersion analysis of simulation results.

Factors	Calculated value of *F*-Fisher criterion	Table value of Fisher's *F*-test
Number of trees on the working zone	511.414	4.84
Number of thin trees in the working zone	134.869	4.84
The average volume of large-sized tree stick	36.203	4.84
The average volume of thin tree stick	27.463	4.84

As can be seen from the comparison of calculated and tabular values of Fisher's *F*-criteria, all factors are significant at the level of $p = 0.05$.The greatest impact on productivity is the total number of trees and the number of thin trees on the working zone. These factors have been identified as variable for further research. In a series of experiments, the results of which are presented in the article, the volume of large-sized and thin trees were taken as averages. The experiment-planning matrix of the first series is shown in table 3.

Table 3. Planning matrix of the first series of simulation experiments.

Factors	Levels of variation of factors		
	min	average value	max
Number of trees on the working zone, trees	6	8	10
Number of thin trees in the working zone, trees	1	3	5
The average volume of large-sized tree stick, m^3	0.5	0.5	0.5
The average volume of thin tree stick, m^3	0.0467	0.0467	0.0467

Figure 3 shows the dependence of the productivity per shift of the FBM on the total number of trees in the working zone (2 – case). The graph shows three curves obtained for 1, 2 and 5 thin trees within the working zone. As follows from the graph, the productivity per shift of the FBM grows with the increase of the number of trees within the working zone for any number of thin trees. This was to be expected, as per unit volume of harvested wood with the increase of the number of trees within working zone, less time is spent on unproductive moving of the FBM from one working zone to another.

At the same time, with an increase of thin trees in the total number of trees within the working zone, there is a decrease in the productivity of the FBM. This is clearly seen from the graph in figure 4 (2 – case). From this, we can conclude, that due to the small volume and small number of thin trees in the working zone, the operation of the FBM, working in the case 2, does not allow achieving the same productivity as on the harvesting of large-sized trees.

These conclusions are well illustrated by the graph in figure 5. This graph shows the curves for five thin trees within the working zone and for different cases of the FBM operations.

As follows from the graph in figure 5, the productivity of the FBM grows with the increase of the number of trees within the working zone in all operating cases. Note, that the lowest productivity the FBM is shown when the joint harvesting of large-sized and thin trees (3 - case), when the trees are cut down and put in packs one by one. The highest productivity of the FBM is achieved when harvesting only large-sized trees (1 - case). These results are expected. You can explain the dependence for the case 2, which takes an intermediate value. With an increase in the average volume of thin trees and a decrease in the average volume of large-sized trees, it can be expected that the FBM productivity will approach with harvesting only large-sized trees (1 - case) and harvesting large-sized trees with thin trees (2 - case).

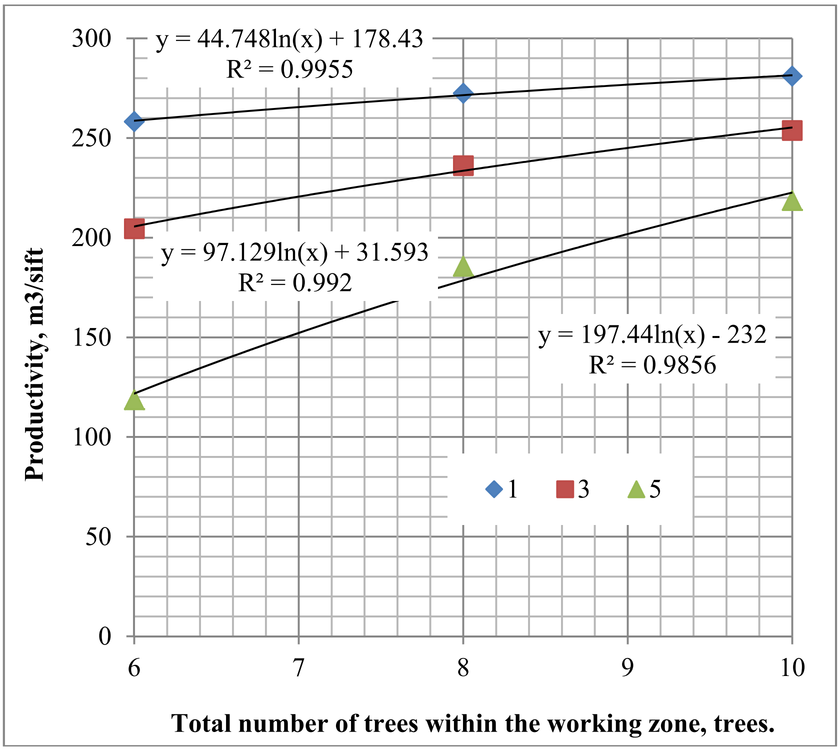

Figure 3. The FBM productivity per shift from the total number of trees within the working zone with 1, 3 and 5 thin trees in the zone.

In order to determine the impact of the volume of large-sized and thin trees on the productivity of the FBM, a series of simulation experiments was planned (table 4).

Figure 6 shows the dependence of the productivity of the FBM from the average volume of the large-sized tree stick with deferent average volume of thin tree stick in case 2 (table 4). On the graph, for comparison, the curve of the productivity of the FBM with the harvesting of only large-sized trees (1 - case) is imposed.

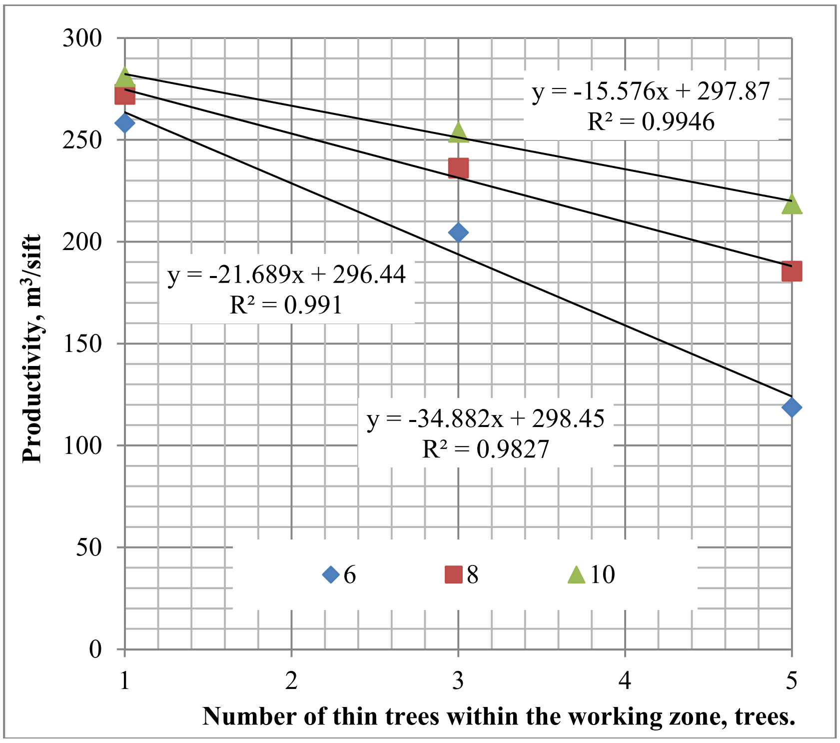

Figure 4. The FBM productivity per shift from the number of thin trees within the working zone with 6, 8 and 10 total number of trees in the zone.

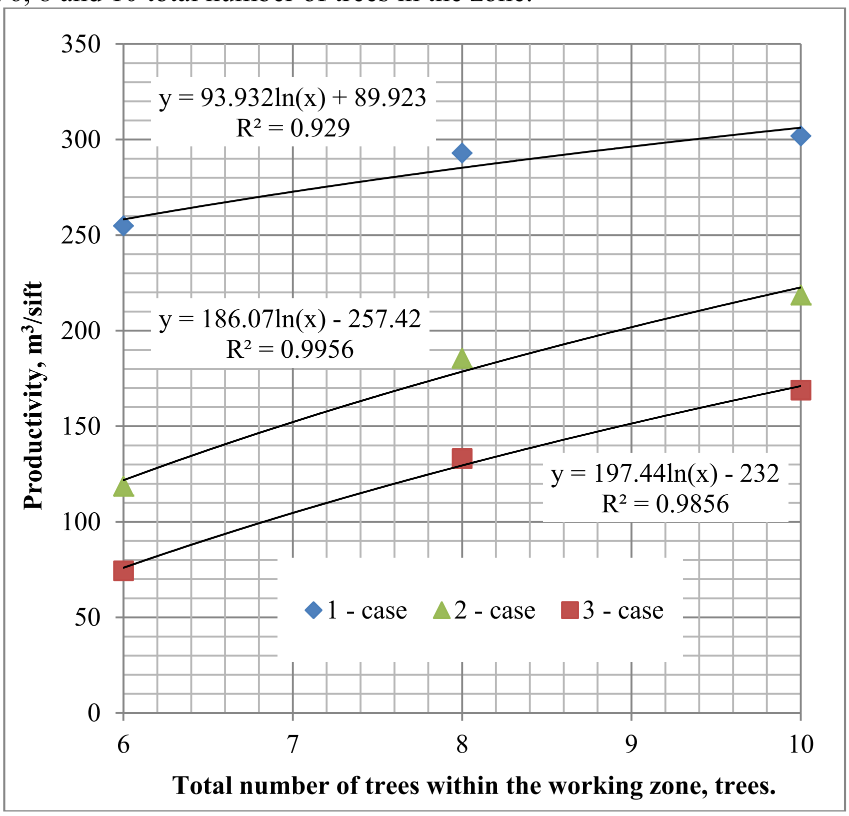

Figure 5. The FBM productivity per shift from the total number of trees within the working zone with 5 thin trees in the zone.

Table 4. Planning matrix of the second series of simulation experiments.

Factors	**Levels of variation of factors**		
	min	average value	max
Number of trees on the working zone, trees	10	10	10
Number of thin trees in the working zone, trees	5	5	5
The average volume of large-sized tree stick, m^3	0.26	0.42	0.58
The average volume of thin tree stick, m^3	0.10	0.18	0.26

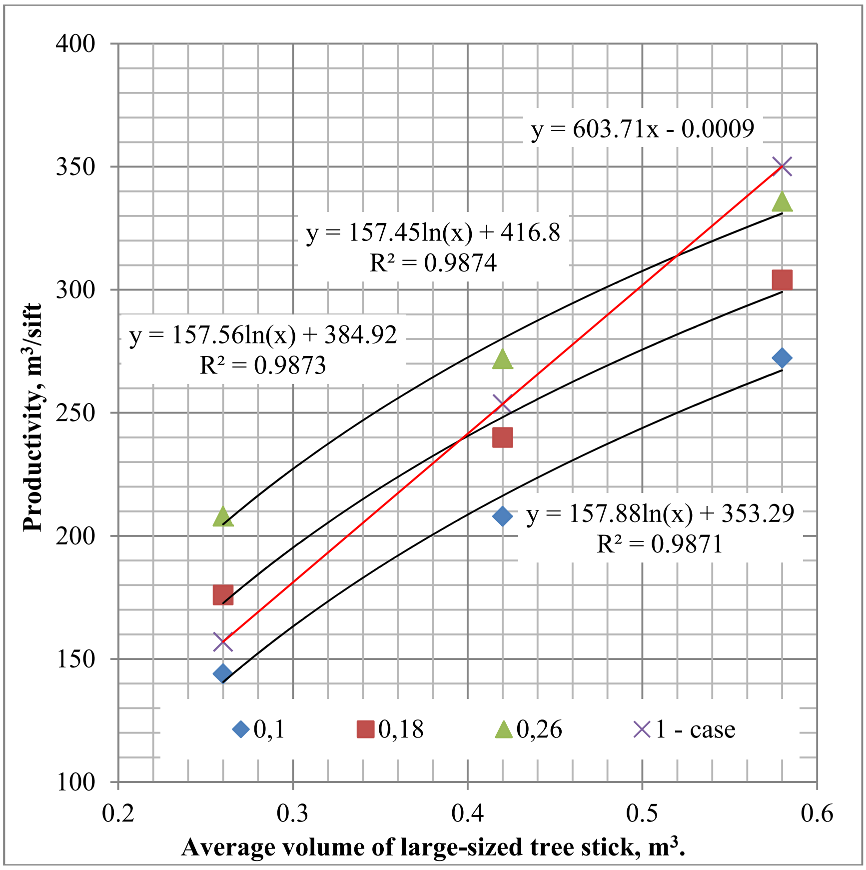

Figure 6. The FBM productivity per shift from the average volume of large-sized tree stick with 5 thin trees in the zone (average volume of thin trees is 0.1, 0.18, and 0.26m^3).

As follows from the graph, with average volumes of large-sized trees close to the volume of thin trees, the productivity of the FBM operating in case 2, can not only be comparable to the productivity of this machine on the harvesting only large-sized trees (1 - case), but even exceed it. For example, while the average volume of the large-sized tree less than 0.4 m^3 and thin tree is 0.18 m^3, the productivity of the FBM in case 2 exceeds the productivity of this machine, operating in a case 1 without harvesting thin trees (figure 6).

4. Summary

The results of the research carried out in this article allow us to draw the following conclusions. Dispersive data analysis of simulation experiments showed that the most significant factors when working the FBM are the total number of trees within the working zone, the number of thin trees within the working zone, the average volume of large-sized tree stick and the average volume of thin tree stick.

Experiments have shown that the FBM productivity increases with the number of trees within the working zone with any number of thin trees (case - 2). At the same time, with an increase of thin trees in the total number of trees within the working zone, there is a decrease in the productivity of the FBM.

The FBM productivity grows with the number increase of trees within the working zone in all operating cases. The lowest performance of the FBM is shown with the joint harvesting of large-sized and thin trees in case 3, when trees are cut and placed in pack one by one. The highest productivity of the FBM is reached in the harvesting only large-sized trees.

With average volumes of large-sized trees close to the volume of thin trees, the productivity of the FBM operating in case 2, can not only be comparable to the productivity of this machine on the harvesting only large-sized trees (case - 1), but even exceed it. For example, while the average volume of the large-sized tree less than 0.4 m^3 and thin tree is 0.18 m^3, the productivity of the FBM in case 2 exceeds the productivity of this machine, operating in case 1 without harvesting thin trees.

In practice it is possible to recommend joint harvesting of large-sized and thin trees only in case 2, when the average volume of the large-sized tree stick does not exceed the two volumes of thin trees.

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