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ANALYSIS OF THE ENERGY EFFICIENCY OF LOGGING AND LOGISTICAL OPERATIONS

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ABSTRACT

Logging operations aimed at obtaining tree biomass include the sequential processing of a tree to produce stem wood and forest residues (stumps, tree roots etc.). Depending on the specialization of a production company, the processing depth of tree biomass may vary considerably. The purpose of this research is to analyze the energy efficiency of the technological process of the tree biomass production at different depth of the tree processing. To ensure the comparability of the results received, the basic hardware was used. The model experiment was based on the production-and-training forestry under the Volga State University of Technology. In this research the generic mathematical model for determining the energy efficiency of the tree biomass production at different processing depth of tree was developed. Evaluation of the energy efficiency of the tree biomass production at different depths of the whole tree processing made it possible to identify the most energy-consuming technological operations. These values depended on the parameters of machines allow us to estimate the level of energy perfection of each certain process. Introduced approach can further analyze the possible alternatives for the application of machine and equipment within the overall tree biomass production process.

Keywords: energy efficiency, logging, mathematical modelling, tree biomass logistics

INTRODUCTION

The extensive use of tree biomass as a renewable raw material for building, woodworking, fuel and energy, health, agriculture and other industries has led to a significant increase in the amount of wood processing. The choice of a logging method influences the form of produced tree biomass. It can be obtained in the form of a whole tree; of a pre-processed tree in the form of a tree length; of assortments and forest residues (stumps, tree roots etc.); and of biomaterial (method for wood chips obtaining). As a result, depending on the form of tree biomass obtained different hardware for loading and removal of logs to the consumer are used.

In the process of establishment of the forestry sector, the efficiency of a particular logging method assessed primarily on the productivity of machinery and equipment (Baranovskij and Nekrasov, [6]; Makuev *et al*., [14]; Nemcov, [16]; Sukhikh, [22]), as well research was done to improve the hardware productivity (Aleksandrov, [1]; Aleksandrov, [3]; Orlov, [17]; Perfilov, [19]).

At the moment, for the purpose of oil dependence weakening, the task of the energy efficiency enhancement of logging and logistics of tree biomass gains in increasing importance (Anderson, [4]; Anisimov and Semenov, [5]; Elizarov, [9]; Jenkins and Sutherland, [10]; Kuznecov, [13]; McCullough, [15]; Pantaleo and Shah, [18]; Shirnin *et al*., [21]; Valyazhonkov *et al*., [23]; Yoshioka, [25]).

Ensuring of the efficiency of logging operations and tree biomass logistics is a complex task, which requires the systematic approach.

The application of integrated solutions is directly connected with the use of the preliminary research works carried out based on deep analysis of the production base of a timber company, of the multivariate assessment of logistical systems and the possible variation of transport and technical equipment structure (Aleksandrov, [2]; Klinov, [11]; Redkin, [20]; Shirnin *et al*., [21]; Yakimovich, [24]).

Such auxiliary factors as the processing depth and the portion of forest residues in the total amount of tree biomass should be taken into account (Bazmi and Zahedi, [7]; Dietrich, [8]; Kolesnikova, [12]).

The purpose of this research is to analyze the energy efficiency of the technological process of the tree biomass production at different processing depth of raw materials.

Research tasks:

1) The development and formalization of initial data of the technological process of the tree biomass production;

2) The building of the generic mathematical model for determination of the energy efficiency of the tree biomass production at different raw material processing depth;

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3) Analysis of the energy efficiency of the intermediate technological processes of the tree biomass production;

4) Assessment of the energy efficiency of the tree biomass production depending on the raw material processing depth;

5) Comparative analysis of the energy efficiency of two alternatives of the tree biomass production.

MATERIALS AND METHODS

As a working area approved the wood cutting area of the production-and-training forestry under the Volga State University of Technology. The basis of the technological process of the tree biomass production is a tree-length method, including the following basic operations: cutting and felling of a tree; skidding; cutting branches and treetops; loading and removal of logs.

A distinctive feature of the considered technological processes alternatives for the tree biomass production with different processing depth is the execution of the technological operations with forest residues. For companies providing processing of a whole tree including tree length processing, branches and tops cutting, the technological operations include additional preparation and removal of forest residues. Another technological process alternative allows for the whole trees removal with disposal of forest residues at the loading site.

For the development and formalization of initial data of the tree biomass production process (Figure-1), a raw data block is formed:

- Alternative A: cutting and felling of a tree; skidding; cutting branches and treetops; loading of tree lengths to a log truck; the formation of forest residues into mounds; tree lengths logistics.

- Alternative B: cutting and felling of a tree; skidding; cutting branches and treetops; loading of tree lengths to a log truck; the formation of forest residues into mounds; loading of forest residues to a truck; tree lengths and forest residues logistics.

Machines for the tree biomass production:

A) Logging operations

- cutting and felling of a tree - felling and milling machine (LP-19);

- skidding - skidding track-type machine with gripping device (LT-154A);

- cutting branches and treetops - gasoline-powered saw (Partner 350);

- loading of tree lengths and forest residues - jaw-loading dipper (PL-1G);

- formation of forest residues into mounds - jaw-loading dipper (PL-1G).

B) Logistics

- log truck 5960-10 based on Ural 43204-1111-31;

- truck MSK-20 based on KAMAZ 6520 with a container K-27.

Figure-1. Two alternatives of the tree biomass production.

The values of taken parameters are shown in Table-1.

In order to simplify the generic mathematical model for determining the energy efficiency of the tree biomass production, we introduce the following assumptions:

- The subject of research for the logging operations of the tree biomass production is an estimated tree;

- The biomass volume of branches and treetops is constant and depends on the tree parameters;

- The average distance of the tree biomass removal, the machines speed and other factors that affect the energy efficiency of logistical operations are constant;

- The calculation of the energy efficiency of the intermediate logging operations is carried out with the direct expenditure of fuel and energy resources of machinery and equipment;

- The technology for the tree biomass production does not vary during the study.

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Table-1. The values of the technological process parameters.

No.	Formalizable object	Parameter	Value
	Estimated tree	Density, kg/m^3	800
		Average tree volume, m^3	0.5
		Mass distribution coefficient in the butt part	0.6
	Cutting and felling of a tree	Weight of a machine, kg	24 300
		Average cycle time, s	40
		Average number of trees, cut during one technological stay	5
		Travel distance, m	10
		Running resistance coefficient	0.25
	Skidding	Weight of a machine, kg	14 600
		Average skidded trees volume, m^3	6.25
		Lifting height of butts, m	2
		Skidding distance, m	100
		Machine running resistance coefficient	0.25
		Trees running resistance coefficient	0.8
	Branches and treetops cutting	Cutting specific work, MJ/m^3	48
		Cut volume, m^3 (20 pcs. 0.01 m each)	0.00157
		Knot volume, % relative to whole tree volume	20
		Treetop volume, % relative to whole tree volume	10
	Tree lengths loading	Weight of a machine, kg	13 800
		Average tree volume, m^3	3.75
		Overrun, m	10
		Lifting height, m	3.5
		Machine running resistance coefficient	0.2
	Formation of forest residues into mounds	Weight of a machine, kg	13 800
		Volume of forest residues mounds, m^3	4.5
		Overrun, m	20
		Machine running resistance coefficient	0.2
	Tree lengths removal	Weight of a machine, kg	12 740
		Weight of tree lengths, kg	15 000
		Average speed, km/h	70
		Frontal surface area, m^2	8
		Aerodynamic resistance coefficient	0.7
		Machine running resistance coefficient	0.02
	Forest residues removal	Weight of a basic machine, kg	9500
		Weight of special equipment, kg	3000
		Volume of a container, m^3	27
		Weight of forest residues, kg	9000
		Average speed, km/h	80
		Frontal surface area, m^2	8
		Aerodynamic resistance coefficient	0.6
		Machine running resistance coefficient	0.02

Building of the generic mathematical model for determining the energy efficiency of the tree biomass production is based on the calculation of energy expenditure of each process stage.

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The work of a felling and milling machine (A_{FMM}) done during cutting and felling of trees includes the energy expenditure for the direct cutting cycle (A_{CC}) and travel to the next technological stay (A_{TS}):

$$A_{FMM} = A_{CC} + A_{TS} = \sum_{j=1}^{N} \int_{V_1}^{V_2} p_{equiv\,j} dV_j + \int_{S_1}^{S_2} P_{FMM} dS_{FMM} \quad (1)$$

Where, N is the number of working operations done by an operator in the course of cutting; $p_{equiv\,j} = \sqrt[3]{\sum_{i=1}^{n} p_i^3 \frac{t_i}{t_{total}}}$ is the equivalent pressure in the hydraulic system of a felling and milling machine in the course of the direct cutting of the j-th tree; p_i is the pressure in the hydraulic system of a felling and milling machine during the period i; t_i is the running time of the hydraulic system of a felling and milling machine under pressure p_i; t_{total} is the total running time of the hydraulic system; n is the number of periods, when the hydraulic system is running under pressure p_i; dV_j is the volume change of the hydraulic engine involved in the direct cutting of the j-th tree; P_{FMM} is the tangential tractive effort on tracks of a felling and milling machine; dS_{FMM} is the travel of a felling and milling machine.

The work done in the process of skidding (A_{SKID}) includes the energy expenditure for tree packing (A_{PACK}), trees skidding (A_{SKID}) and returning of an empty machine ($A_{SKEmpty}$):

$$A_{SKID} = A_{PACK} + A_{SKID} + A_{SKEmpty} = \sum_{k=1}^{K} \int_{V_1}^{V_2} p_{equiv\,k} dV_k + \int_{S_1}^{S_2} P_{SKID} dS_{SKID} + \int_{S_1}^{S_2} P_{SKEmpty} dS_{SKEmpty} \quad (2)$$

Where, K is the the number of the working operations carried out by an operator in the collection of tree packs; p_{equivk} is the equivalent pressure in the hydraulic system of a skidding machine in the collection of the k-th tree pack; dV_k is the change in volume of the hydraulic engine involved in the tree packing; P_{SKID} и $P_{SKEmpty}$ are the tangential tractive effort on tracks of a felling and milling machine at skidding and returning of an empty machine, respectively; dS_{SKID} and $dS_{SKEmpty}$ are the travel of a felling and milling machine at skidding and returning of an empty machine, respectively.

Branches and treetop cutting (A_{BTC}) is determined by the specific work of cutting (Shirnin, 2004).

The energy expenditure taken place during the loading of tree lengths (A_{TLL}) and forest residues (A_{FR}) are defined as the energy expenditure for the trees lift (A_{lift}), the travel with the trees pack (A_{ttp}) and the returning of an empty machine ($A_{TLLempty}$):

$$A_{TLL} = A_{lift} + A_{ttp} + A_{TLLempty} = \int G_{pack} dh + \int_{S_1}^{S_2} P_{TLLskid} dS_{TLLskid} + \int_{S_1}^{S_2} P_{TLLempty} dS_{TLLempty} \quad (3)$$

Where, G_{pack} is the weight of the trees pack; dh is the lifting height of the trees pack; $P_{TLLskid}$ and $P_{TLLempty}$ are the tangential tractive effort on tracks of a loading machine at skidding and returning of an empty machine, respectively; $dS_{TLLskid}$ and $dS_{TLLempty}$ are the travel of a loading machine at skidding and returning of an empty machine, respectively.

Similarly, the energy expenditure for loading of forest residues are determined (A_{FRL}).

The work done when disposing forest residues at the loading area (A_{FRD}) consists of the energy expenditure for formation of forest residues into mounds (A_{FFRM}) and idling expenditure (A_{idle}).

$$A_{FRD} = A_{FFRM} + A_{idle} = \int_{S_1}^{S_2} P_{FFRM} dS_{FFRM} + \int_{S_1}^{S_2} P_{idle} dS_{idle} \quad (4)$$

Where, P_{FFRM} and P_{idle} are the tangential tractive effort on tracks of a machine during the formation of forest residues into mounds and the idling, respectively; dS_{FFRM} and dS_{idle} are the travel of a machine during the formation of forest residues into mounds and the idling, respectively.

Total energy expenditure connected with the travel of machines, including the energy expenditure for travel of a felling and milling machine (A_{FMM}); skidding (A_{SKID}) and return of an empty machine ($A_{SKempty}$); travel of loading machine with the trees pack (A_{ttp}) and return of an empty machine ($A_{TTLempty}$); formation of forest residues into mounds (A_{FFRM}) and loading machine idling (A_{idle}); logistics of tree lengths (A_{TLL}) and forest residues (A_{FRL}) when trucks are loaded, and logistics of a log truck (A_1) and the truck MSK-20 (A_2) when they are empty, will be determined on the basis of the methodology for determining the tangential tractive effort on the leading elements of transport and technological machines and the average travel distance.

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RESULTS

The calculation of the energy efficiency of the intermediate processes of the tree biomass production is carried out in two stages. In the first stage, the estimation of the energy expenditure for each technological operation based on technical parameters of machines or equipment as well as on the formalized parameters of the working process is performed.

In the second stage, the obtained values of the energy expenditure will be grouped under conditions of the production process (alternative A or alternative B).

The results of the technological processes modelling of the tree biomass production

Taking into account the relations (1) - (4) of the generic mathematical model for determining the energy efficiency of the tree biomass production at different processing depth of raw materials and predetermined initial data, the values of the energy expenditure of each technological process were obtained. The results are shown in Table-2.

Table-2. Total energy expenditure for technological processes, MJ.

A_{FMM}	A_{SKID}	A_{BTC}	A_{TLL}	A_{FRL}	A_{FRD}	A_{TLL}^*	A_{FRL}^*	A_1^*	A_2^*
13.98	9.53	0.07	0.70	0.74	1.65	75.45	68.81	46.02	48.15

Note. * – for travel distance of 10 km.

The greatest energy expenditure to perform logging operations when producing tree biomass takes place during the felling and milling machine operation - 13.98 MJ. The lowest one is needed for branches and treetop cutting - 0.07 MJ.

In the generic cycle of the tree biomass production the greatest value of energy expenditure is connected with logistical operations - 75.45 MJ is for removal of tree lengths and 68.81 MJ is for removal of forest residues. In addition, the energy expenditure for unloaded travel of transport vehicles is also great enough (46.03 MJ is for log truck 5960-10 and 48.15 MJ is for the truck MSK-20 for the travel distance of 10 km).

Absolute values of the energy expenditure for performance of individual technological operations shown in Table 2 are not convenient for their processing because the numerical values depend on the volume of the subject of research. Traveling and processing different amounts of tree biomass, not comparable values of energy expenditure are obtained. To obtain comparable data we need to calculate the specific indicators of the technological process, which are related to the unit volume of tree biomass.

The specific energy expenditure of the technological operations with the *j*-th tree (A_j) is defined as the ratio of total energy expenditure (A_{total}) to the cubage of the *j*-th estimated tree (V_j):

$$A_j = A_{total} / V_j \, . \tag{5}$$

The specific energy expenditure of the technological operations with tree lengths (A_{TL}) is determined by taking into account the loss of the tree volume in the process of branches and treetop cutting. The value of A_{TL} will be more than the value of A_j, as it was chosen a tree growing at the cutting area as an estimated one (Aleksandrov, 2002):

$$A_{TL} = \frac{A_j}{(100\% - \%branches - \%treetops)/100\%} \, . \tag{6}$$

When comparing the energy expenditure for the tree biomass production we use two alternatives of production, as shown in Figure-1. Alternative A is based on use of only tree length wood, alternative B is focused on the further processing of forest residues.

The results of calculation of the specific energy expenditure for two alternatives of the tree biomass production are presented in Figure-2.

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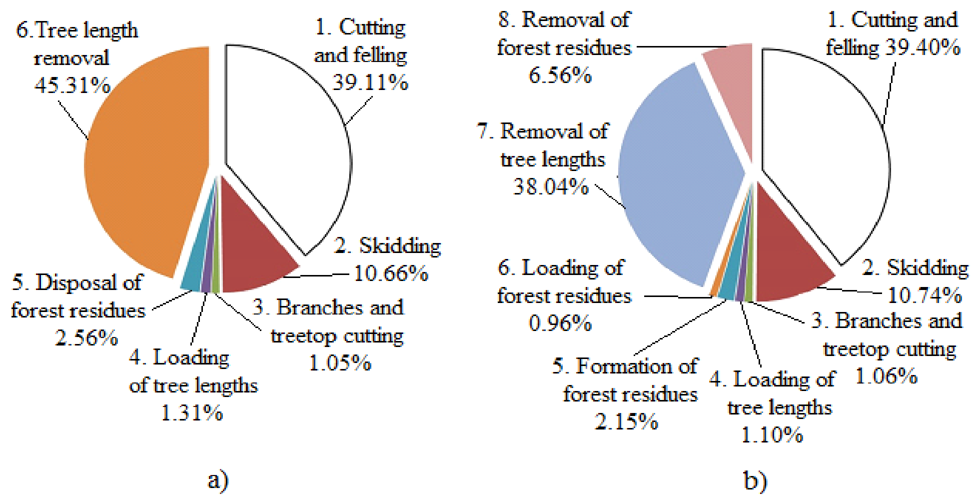

Figure-2. Specific energy expenditure at the travel distance of 10 km:
a) for enterprises with the processing of tree lengths according to alternative A;
б) for enterprises with the processing of whole trees according to alternative B

Calculations show that about 39% of the specific energy expenditure of the tree biomass production is the share of the technological operations connected with cutting and felling of a tree. The shares of the removal of tree lengths according to the production process of alternative A and alternative B are 45.31% and 38.04%, respectively.

Using the specific indicators of energy expenditure allows more clearly estimate the impact of certain technological operations of the tree biomass production. These values describe a set of technical indicators of a certain process, including the amount of processed trees, processing speed, possible energy expenditure for auxiliary work and standing idle.

The results of comparative analysis of the energy efficiency of the tree biomass production using two alternatives of production processes

Energy efficiency estimation of the tree biomass production depending on the processing depth is performed on the basis of the technological operations list, which is different at alternative A and alternative B.

To perform the analysis we use a coherent approach for determining the energy expenditure of certain process operations for the tree biomass production. In the second stage, we will compare the energy efficiency of the production according to alternative A and alternative B with a condition of an equal volume of produced tree biomass.

In view of the received data, the nearest multiple of the volume of transported cargo amounted to 337.5 m^3. This value is defining for the number of cycles performed for each technological operation. See Table-3.

In view of the number of cycles performed, we calculate the energy expenditure for technical operations with the help of the generic mathematical model presented above. The calculation results are presented in Table-3.

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Table-3. Comparative analysis of the energy efficiency of the tree biomass production.

Description of technological operations	Number of cycles	Energy expenditure, MJ	
		Alternative A	Alternative B
1. Cutting and felling of a tree	135	1887.29	1887.29
2. Skidding	54	514.38	514.38
3. Branches and treetop cutting	270	20.35	20.35
4. Loading of tree lengths	90	63.30	63.30
5. Formation of forest residues into mounds	75	123.61	123.61
6. Loading of forest residues	90	-	66.22
7. Removal of tree lengths*	18	2186.64	2186.64
8. Removal of forest residues*	8**	-	911.76
Total		4795.57	5773.55
Specific energy expenditure, MJ/m^3		14.21	13.51

Note. * – for travel distance of 10 km; ** – in view of the volume of branches and treetops.

The results of comparative analysis of the energy efficiency of the tree biomass production applying two alternatives of the production process in absolute terms indicate a high level of energy expenditure of production when applying alternative B. In comparison with using only tree length wood with disposal of forest residues at the loading site (Alternative A), the energy expenditure of processing the whole tree (Alternative B) is 977.77 MJ more.

However, if you use the specific indicators of energy expenditure, due to the larger volume of processed tree biomass, the processing of a whole tree (Alternative B) is more advantageous, which uses 0.7 MJ / m^3 less energy expenditure than when processing only stem part of a tree.

DISCUSSIONS

Solving the current problem of integrated evaluation of the tree biomass production, we used the value of energy expenditure of logging and logistical processes as a criterion for energy efficiency. To ensure the comparability of the data obtained, we used the initial data based on the use of the same natural and production base of the timber-processing complex. The values of variable parameters depend on different processing depth of raw materials.

By the solving of the assigned tasks the generic mathematical model for determining the energy efficiency of the tree biomass production at different processing depth of raw materials was developed. This model is based on the use of repeatedly tested physical models of vehicle traffic on prearranged roads (logistics), lifting and traveling of the subject of research with the intermediate processing (logging operations). The accuracy of the obtained data is comparable with an accuracy of initial data determining and is less than 8% in comparison with the real values obtained.

Through the analysis of the energy efficiency of the intermediate technological processes of the tree biomass production, the energy expenditure for each process operation was determined. These values depend on the parameters of machines and allow us to estimate the level of energy perfection of each certain process. This approach can further analyze the possible alternatives for the application of machine and equipment within the overall production process. In addition, it is possible to formulate a list of requirements for manufacturers of timber and transport vehicles to provide the necessary technical and economic indicators.

Evaluation of the energy efficiency of the tree biomass production at different depths of the whole tree processing made it possible to identify the most energy-consuming technological operations. For the logging process, they are cutting and felling of a tree (approximately 39% of the total share). For logistics of tree biomass, they are removal of tree lengths - 45.31% and 38.04% according to the production process of alternative A and alternative B, respectively.

A comparative analysis of the energy efficiency of the tree biomass production according to two alternatives of the production process on the basis of equal production program has shown that the specific energy expenditure of the whole tree processing, including the beneficial use of stem wood, treetops and branches, amount to 13.51 MJ per cubic meter of wood harvested. This figure is 0.7 MJ/m^3 less than the value of the energy expenditure when processing tree lengths only.

In absolute terms, more advanced processing of tree biomass requires the introduction of an additional process of forest residues removal. To implement the production process based on the use of stem wood only, it requires works on disposal of forest residues, which also lead to intake of additional resources and may adversely affect the ecological system.

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