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OPTIMISATION OF THE DESIGN AND OPERATION CAPACITIES OF MOBILE CUTTING AND MANIPULATION SYSTEM TO MINIMISE SOIL DISTURBANCE AND CONTAMINANT LOAD IN FORESTS

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ABSTRACT

The main subject of the article is optimisation of the design and operation capacities of mobile cutting and manipulation systems functioning in a forest ecosystem. Conditions were found to minimise the product volume related erosion.

The production system analysed is taken as that one with incoming flows of material and energy. The design and operational capacities are governing quantities for the system operation. The amount of cutting-manipulation erosion per unit volume of biomass worked (i.e. erosion related to the volume of cut and manipulated wood; related erosion) was one of the most important analysed factors.

System and mathematical analysis of the criterion function was accomplished. The optimum capacities of mobile field systems at which the minimum related erosion is reached were determined. The theoretical findings were verified in an experiment.

Key words: forest ecosystems; economy; ecology; system analysis; mathematical modelling erosion.

INTRODUCTION

Processes of cutting-manipulation and water erosion cause devastation of forest ecosystem soils [9]. This results in reduction of ecosystem production, extra-production functions as well as surface water contamination. The exposure of forest soils to damage is becoming more important mainly in the regions with increased emissions, especially where growth declines as consequence of extensive air polluting extractions [8].

The use of heavy equipment for cutting and manipulation as well as for forestation soil treatment became more popular mainly in the mountainous emission regions. Owing to this the increased erosion devastation of surfaces of forest ecosystems is revealed [9]. Not only shortage of forest soils is the consequence of the increased erosion but also soil degradation arises. And thus both physical and chemical properties as well as soil water relations deteriorate [2].

Forestry-technical precautions are most relevant anti-erosion measures applied in the prevailing areas of endangered soils [7]. The precautions consist of a selection [4] of convenient, environment-friendly technologies and equipment as well as in the equipment exploitation at the right capacities.

In the submitted paper we present both the theoretical analysis of the problem and the method of determination of the optimum system capacities for the work at minimum erosion (erosion related to the volume of cut and manipulated wood, i.e. processed wood; related erosion). The present study has linkage to some results of an earlier analysis of the cutting system [3]. The relationship "related erosion – system capacity" served as the main criterion function for capacity optima calculations. The results obtained were experimentally tested by the evaluation of the cutting-manipulation erosion produced in the course of the operation of Swedish systems TERRI 20-20 and TERRI 20-40. Physical meanings of members and quantities of the criterion function are explained in this study.

QUALITATIVE SPECIFICATION OF FACTORS INFLUENCING THE CUTTING-MANIPULATION EROSION

If we analyse various equipment systems of forest woodworking designed for various capacities we can see that different consumption of specific energy or material is amounted to, the cutting-manipulation erosion being proportional to consumption.

1. Factors influencing specific energy and material consumption

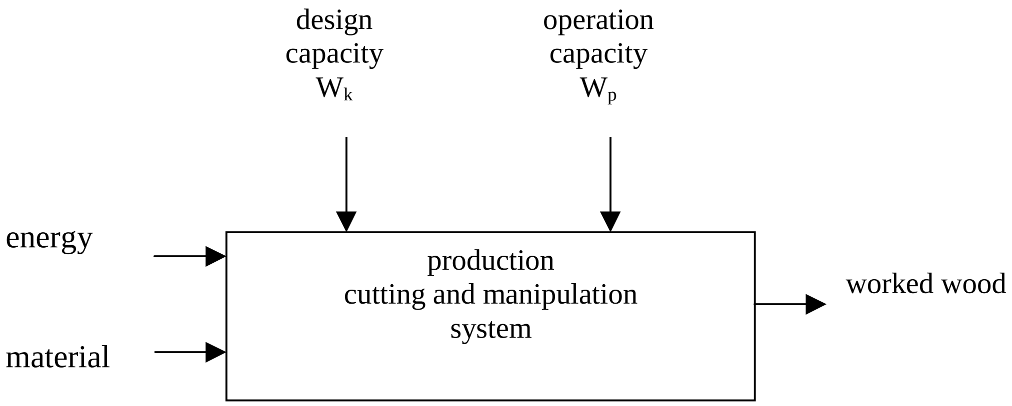
    a) Dimensional and weight changes of cutting and manipulation machine elements, which influence energy, material and work demands, are not proportional to capacity.
    b) Changes in investment demands are not proportional to the capacity changes. The unification of machine parts influences this problem and leads usually to some overestimation.
    c) Dimensional changes of apertures and throughways (usually accompanying the dimensional changes of material flows in cutting and manipulation systems) which come with capacity changes do not always influence proportionally the energy, material demands and cutting-manipulation erosion. In general, erosion is a function of the section and speed of material flow.

Therefore, the design way used for the system capacity enhancement has to be assumed during more detailed analyses of influence of above-mentioned factors.

2. Enhancement possibilities of the design capacity of forestry systems

    a) Material flow or catch width enhancement
        - with help of the enhancement of number of working elements (e.g. shares or blades, sections of cutting mechanisms of planter)
        - with help of the dimension extension of working elements or parts (e. g. length of cutting apparatus)
    b) Cross section enhancement of material flow in transport ways. The cross sectional form can be kept or changed (cutting apparatus, manipulation mechanism)
    c) Enhancement of maximum operation capacity

Fig. 1. Scheme of cutting and manipulation system



OPTIMUM OPERATION MODE OF CUTTING MANIPULATION SYSTEM FROM THE VIEWPOINT OF SPECIFIC EROSION RELATED TO THE UNITY OF CAPACITY

Energy and material enter the cutting and manipulation systems in the course of their operation. Both energy and material undergo transformations. The resulting product, worked wood, is the result of those transformations (see Fig. 1). The rate control of the system's work is realized by using controllers that set the magnitudes of both capacities.

As was already stated the cutting-manipulation erosion arises in the course of the work of cutting and manipulation systems. This erosion is a process rate dependent phenomenon. In principle, it is an indirect expression of some kind of energy losses in the studied process.
It holds for the amount of cutting-manipulation erosion M_{EF} that is a consequence of energy transformations:

$$M_{EF} = \frac{m_E . Q_E}{\eta_{CE}(W_K, W_p)} . S_E \qquad \text{(kg)} \qquad (1)$$

M_{EF}	–	amount of cutting-manipulation erosion occured in the course of cutting and manipulation system due to energy transformation	(kg)
m_E	–	amount of energy carrier consumed (diesel, gasoline)	(kg)
W_p	–	system operation capacity	$(m^3 \cdot s^{-1})$
W_k	–	system design capacity	$(m^3 \cdot s^{-1})$
S_E	–	specific inherent erosion arisen due to energy transormation in the process in	$(kg \cdot J^{-1})$
Q_E	–	specific energy of energy carrier	$(J \cdot kg^{-1})$
η_{CE}	–	energy transformation efficiency in the process way up to the resulting product in dependence on design and operation capacities	(-)

The total energy A consumed in the process for the realization of the total production of W_C is as follows:

$$A = \frac{m_E \cdot Q_E}{\eta_{CE}(W_p, W_k)} \qquad \text{(J)} \qquad (2)$$

where

A	–	energy used in the production process	(J)
Q_E	–	specific energy of the energy carrier	$(J \cdot kg^{-1})$
W_p	–	cutting and manipulation system operation capacity	$(m^3 \cdot s^{-1})$
W_k	–	system design capacity of the same system	$(m^3 \cdot s^{-1})$

The total product amount obtained by the transformation of the energy A in the system is

$$W_{CE} = \frac{m_E \cdot Q_E}{Q_V \eta_{CE} \cdot (W_K, W_p)} \qquad (m^3) \qquad (3)$$

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where:

W_{CE} – total product amount resulting from the energy transormation in the system, in (m^3)
Q_V – specific energy demand by cutting and manipul. system per product unit, in $(J \cdot m^{-3})$

The total product amount from the transformation of incoming materil at amount m_M is

$$W_{CM} = \frac{m_M}{Q_M \cdot \eta_{CM}(W_K, W_P)} \qquad (m^3) \qquad (4)$$

where

W_{CM} – total procuct amount resulting from the material transformtion in the system, in (m^3)
m_M – total amount of material income
Q_M – incoming material which must be fed into the system per product unit, in (kg)
$\eta_{CM}(W_k, W_p)$ – efficiency of material transformations up to the resulting product in dependence on the capacities W_k, W_p $(kg \cdot m^{-3})$

The cutting-manipulation erosion produced by the system investigated as the consquence of material transormations (e.g. wear of tires due to slipage) is given by

$$M_{EM} = \frac{m_M}{\eta_{CM}(W_K, W_p)} \cdot S_M \qquad (kg) \qquad (5)$$

where:

M_{EM} – amount of the cutting-manipulation erosion due to material transformations, in (kg)
s_M – specific inherent erosion due to material transformations $(kg \cdot kg^{-1})$
m_M – total amount of the material fed into the system (kg)

Since the total product of the system is, in general, given both by energy and material transformation it must hod that the product amounts calculated separately for each of them are equal.

$$W_{CE} = W_{CM} = W_C(W_k, W_p) \qquad (m^3) \qquad (6)$$

$W_C(W_k, W_p)$ – total system product

Presuming Q_E, s_E, η_{CE} constant for the time interval analysed we can express the time derivative of Eq. 1 in the form

$$\frac{\partial M_{EE}}{\partial t} = \frac{\frac{\partial m_E}{\partial t} \cdot Q_E}{\eta_{CE}(W_k, W_p)} \cdot S_E \qquad (kg \cdot s^{-1}) \qquad (7)$$

where

t – time (s)

$\frac{\partial M_{EE}}{\partial t}$ – amount of cutting-manipulation erosion per time unit due to energy transformation $(kg \cdot s^{-1})$

$\frac{\partial m_E}{\partial t}$ – energy carrier amount supplied per time unit $(kg \cdot s^{-1})$

For system capacity we have (see Eq. 6)

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$$\frac{\partial W_C}{\partial t}=\frac{\partial W_{CE}}{\partial t}=\frac{\partial W_{CM}}{\partial t} \qquad (\mathrm{m}^3\cdot\mathrm{s}^{-1}) \qquad (8)$$

Supposing s_M, η_{CM} constant for the time interval analysed we obtain for the time derivative of Eq. 5:

$$\frac{\partial M_{EM}}{\partial t}=\frac{\frac{\partial m_M}{\partial t}.S_M}{\eta_{CM}(W_k,W_p)} \qquad (9)$$

In the last two equations it is

$\frac{\partial W_{CE}}{\partial t}$ – system capacity calculated from the energy transformations $(\mathrm{m}^3\cdot\mathrm{s}^{-1})$

$\frac{\partial W_{CM}}{\partial t}$ – system capacity calculated form the material transformations $(\mathrm{m}^3\cdot\mathrm{s}^{-1})$

$\frac{\partial W_C}{\partial t}$ – system capacity calculated in total $(\mathrm{m}^3\cdot\mathrm{s}^{-1})$

$\frac{\partial M_{EM}}{\partial t}$ – amount of cutting-manipulation erosion per time unit due to material transformation $(\mathrm{kg}\cdot\mathrm{s}^{-1})$

$\frac{\partial m_M}{\partial t}$ – material amount supplied per time unit $(\mathrm{kg}\cdot\mathrm{s}^{-1})$

Summing Eqs. 7 and 9 we obtain erosion amount produced by the system per time unit

$$\frac{\partial M_{EEM}}{\partial t}=\frac{\frac{\partial m_E}{\partial t}\cdot Q_E.S_E}{\eta_{CE}(W_k,W_p)}+\frac{\frac{\partial m_M}{\partial t}\cdot S_M}{\eta_{CM}(W_k,W_p)} \qquad (10)$$

$\frac{\partial M_{EEM}}{\partial t}$ – total erosion amount produced by the system per time unit $(\mathrm{kg}\cdot\mathrm{s}^{-1})$

Finally, we can express specific erosion related to the total product unit dividing Eq. 10 by the total system capacity

$$Q=\frac{\partial M_{EEM}}{\partial t}\cdot\frac{1}{W_C(W_K,W_P)} \qquad (\mathrm{kg}\cdot\mathrm{m}^{-3}) \qquad (11)$$

The extremes of the specific cutting-manipulation erosion (related to the worked wood unity) in the function of W_K, W_P follow form the necessary conditions [1]

$$\frac{\partial^2 M_{EEM}(W_K,W_p)}{\partial t.\partial W_k}=0 \qquad (\mathrm{kg}\cdot\mathrm{m}^{-3}) \qquad (12)$$

$$\frac{\partial^2 M_{EEM}}{\partial t.\partial Wp}=0 \qquad (\mathrm{kg}\cdot\mathrm{m}^{-3}) \qquad (13)$$

After these derivations and simple manipulations we finally obtain formulas that fulfil conditions for the extreme [6]

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$$\frac{f_E}{\eta_{CE}^2(W_p,W_k)}\cdot\frac{\partial\eta_{CE}(W_p)}{\partial W_p}+\frac{f_M}{\eta_{CM}^2(W_p,W_k)}\cdot\frac{\partial\eta_{CM}(W_p)}{\partial W_p}+\frac{\partial W_C(W_p)}{\partial W_p}\cdot f_s\cdot W_C^{-1}(W_K,W_P)=0 \qquad (14)$$

$$\frac{f_E}{\eta_{CE}^2(W_p,W_k)}\cdot\frac{\partial\eta_{CE}(W_k)}{\partial W_k}+\frac{f_M}{\eta_{CM}^2(W_p,W_k)}\cdot\frac{\partial\eta_{CM}(W_k)}{\partial W_k}+\frac{\partial W_C(W_k)}{\partial W_k}\cdot f_s\cdot W_C^{-1}(W_K,W_P)=0 \qquad (15)$$

where

$$f_E=\frac{\partial m_E}{\partial t}.Q_E.S_E \qquad (16)$$

participation rations (math. weihts already involved)

$$f_M=\frac{\partial m_M}{\partial t}.S_E \qquad (17)$$

$$f_s=\left[\frac{f_E}{\eta_{CE}(W_{k,}W_p)}+\frac{f_M}{\eta_{CM}(W_k,W_p)}\right] \qquad (18)$$

f_E – energy flow due to energy transformations (kg·s^{-1})
f_M – energy flow due to material transformations (kg·s^{-1})
f_S – coefficient of synergic effect of energy and material transformations per product unit of the system studied (kg·s^{-1})

Erosion flow due to energy transformation arises in the course of those operations of mobile field systems that mainly process mass (harvesters, processors, machines and equipment for basic soil treatment in forest nurseries). Erosion flow due to material transformation is typical for production machines and power supplies, which bring material into the process (machines for fertilization, sowing, planting, plant protection, nursing etc.).

Coefficient f_S is the measure of synergic effect of contemporaneous transformation of material and energy in the production system. In our study this applies mainly to energy and material losses in consequence of the soil surface and plant canopy injury by slippage, sinking, soil hardening, but also because of machine tires wear, their grinding off and histeresis etc.

DISCUSSION OF THE GENERAL ANALYSIS

The analysis of the formulas for cutting-manipulation erosion extremes [Janeček, 1991] revealed that

$$\frac{\partial\eta_{CE}(W_K,W_p)}{\partial W_p}\rangle 0 \qquad \text{in the region of lower values of } W_P \qquad (19)$$

$$\frac{\partial\eta_{CE}(W_K,W_p)}{\partial W_p}\langle 0 \qquad \text{in the region of higher values of } W_P \qquad (20)$$

$$\frac{\partial\eta_{CE}(W_K,W_p)}{\partial W_K}\rangle 0 \qquad \text{lower values of } W_K \qquad (21)$$

$$\frac{\partial\eta_{CE}(W_K,W_p)}{\partial W_K}\langle 0 \qquad \text{higher values of } W_K \qquad (22)$$

Similar inequalities hold true also for derivatives of η_{CM}

$$\frac{\partial\eta_{CM}(W_K,W_p)}{\partial W_p}\rangle 0 \qquad \text{lower values of } W_P \qquad (23)$$

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$$\frac{\partial \eta_{CM}(W_K, W_p)}{\partial W_p} \langle 0 \qquad \text{higher values of } W_P \tag{24}$$

$$\frac{\partial \eta_{CM}(W_K, W_p)}{\partial W_K} \rangle 0 \qquad \text{lower values of } W_K \tag{25}$$

$$\frac{\partial \eta_{CM}(W_K, W_p)}{\partial W_K} \langle 0 \qquad \text{higher values of } W_K \tag{26}$$

Further, the following inequalities are valid:

$$f_E > 0 \qquad (\text{kg}\cdot\text{s}^{-1}) \tag{27}$$

$$f_M > 0 \qquad (\text{kg}\cdot\text{s}^{-1}) \tag{28}$$

$$\eta_{CE}^2 > 0 \qquad (-) \tag{29}$$

$$\eta_{CM}^2 > 0 \qquad (-) \tag{30}$$

$$\frac{W_C}{\partial W_p} > 0 \quad \text{production system capacity increases with the operation capacity } W_P \tag{31}$$

$$\frac{W_C}{\partial W_K} > 0 \quad \text{production system capacity increases with the design capacity } W_K \tag{32}$$

$$f_S \rangle 0 \tag{33}$$

$$\eta_{CE} > 0 \qquad (-) \tag{34}$$

$$\eta_{CM} > 0 \qquad (-) \tag{35}$$

With the use of inequalities (27-35) we can rewrite Eqs. 19-20 into the form

$$\frac{f_E}{\eta_{CE}^2} \cdot \frac{\partial \eta_{EE}(W_p, W_K)}{\partial W_p} + \frac{f_M}{\eta_{CM}^2} \cdot \frac{\partial \eta_{EM}(W_p, W_K)}{\partial W_p} + \frac{\partial W_{CM}(W_{P,} W_K)}{\partial W_p} \left[\frac{f_E}{\eta_{CE}} + \frac{f_M}{\eta_{CM}} \right] > 0 \tag{36}$$

holding true for $W_P > W_{POPT}$, where W_{POPT} is the optimum capacity. The opposite inequality (left part < 0) holds for the condition $W_P < W_{POPT}$ (Wiener, 1954).

Manipulating similarly Eqs. 21-22 we obtain

$$\frac{f_E}{\eta_{CE}^2} \cdot \frac{\partial \eta_{EE}(W_K, W_P)}{\partial W_K} + \frac{f_M}{\eta_{CM}^2} \cdot \frac{\partial \eta_{EM}(W_K, W_P)}{\partial W_K} + \frac{\partial W_C(W_K, W_P)}{\partial W_K} \left[\frac{f_E}{\eta_{CE}} + \frac{f_M}{\eta_{CM}} \right] > 0 \tag{37}$$

for $W_K > W_{KOPT}$, and again with the opposite inequality holding for the opposite condition, $W_K < W_{KOPT.}$

EXPERIMENTAL VERIFICATION OF THE MODEL

The expected, above derived behaviour of the forest production systems was experimentally proved. The possibility to optimise the system's operational and design parameters from the ecological viewpoint is a very important result for practice.

The measurements of the relationships "soil surface damage – month capacity (in $m^3.month^{-1}$)" were carried out in our experiments because of their much quicker and simpler effectuation (Fig. 2 and Fig. 3). We applied such

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way of erosion estimation having in mind the character of negative effects of forestry field machines as well as the fact the soil damage is a typical point of erosion increase. The sudden exposition of damaged surface to negative factors is time limited, so the mass estimation of the erosion should be almost proportional to what we used.

The forestry systems of the type “energy transducers – operation machines” exploited in cutting, growing and manipulation were used as physical models. The 5 to 15 % reduction of cutting-manipulation erosion was found at the optimum capacities calculated.

The courses of the dependence of “specific erosion-operation capacity” were measured in north Bohemia localities for Swedish sets TERRI 20-20 and TERRI 20-40. The equipment technical data is quoted below:

TERRI 20-20:
motor – Kubota, type DH 850-B, diesel
power output- 17 kW at 3600 rpm
dimensions – length 6500 mm, width 1460 mm, height 2350 mm
weight – 3390 kg
transport weight – 1690 kg
reach of hydraulic hand – 4,2 m

TERRI 20-40:
motor – Kubota, type D 1105, diesel
power output – 17,6 kW at 3000 rpm
dimensions – length 6500 mm, width 1470 mm, height 2250 mm
weight – 4950 kg
transport weight – 2960 kg
reach of hydraulic hand – 7 m

Fig. 2. Specific damage in dependence on system operation capacity for TERRI 20-20

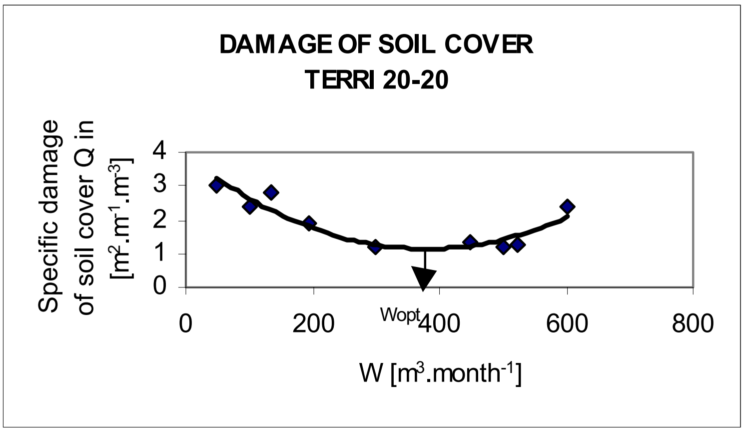
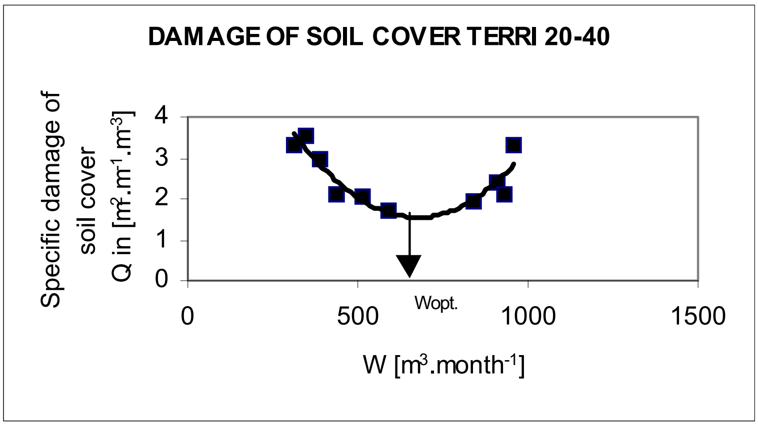


Fig. 3. Specific damage in dependence on system operation capacity for TERRI 20-40



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The equipment set TERRI 20-20 is designed for the work at the capacity range of about 200-400 $m^3.month^{-1}$. The optimum production capacity was about 400 $m^3.month^{-1}$ in local conditions, where experiments were carried out. It is the upper value of the recommended range, but it is applicable. As the minimum cutting-manipulation erosion was found here, TERRI 20-20 should be exploited at the capacity of 400 $m^3.month^{-1}$. The specific cutting-manipulation erosion increased by 15-30 % when operation capacity used differed by 5-10 % from that for the optimum.

Similar conclusions we obtained for TERRI 20-40, only the optimum system capacity moved to about 680 m^3. $month^{-1}$.

CONCLUSIONS

The objective of this study, as stated in the beginning, was the description derivation for the capacity dependence of specific erosion produced by the forest cutting and manipulation systems. The function was derived and it is visible from its physical significance that the erosion flow in the course of the process realized depends on the energy and material transformations in the way up to the resulting product. The synergic effect of both transformations was also involved. It increases the erosion flow and the amount of specific cutting-manipulation erosion (per unit volume of worked wood). So it is logical that the erosion is also system work rate dependent. The system work rate is expressed by the design and operation capacities.

The existence of sharp minimum on the “specific erosion – capacity” dependence was demonstrated mathematically. It is an important theoretical result for practical usage. It means the system exploitation has the ecological optimum.

The experimental verification of the theory showed the sets TERRI 20-20 ad TERRI 20-40 can be exploited at the capacities at which the specific erosion related to volume unit of the worked wood is minimum. The 5-10 % deviation from the capacity optimum if followed by the 15 – 30 % increase in specific erosion.

It is necessary to make a careful choice not only of the equipment design but also its capacity at the exploitation to obtain the maximum ecological purity of the work of forestry mechanization systems.

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