FACTORS OF THE EFFICIENCY OF HARVESTERS AND FORWARDERS IN LOGGING

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Abstract*: The high productivity of harvesters is commonly known. Therefore are the harvester logging technologies increased in the Czech forestry. It is very important to know factors affecting the efficiency not only of harvesters, that do the felling, delimbing, primary extraction and cross-cutting of the wood, but also of forwarders. The forwarders are necessary for the effective transport of wood processed by harvesters. The harvester technologies are used very often in thinning operations, therefore was the research focused on this way of logging. The task of analyse of efficiency factors was solved out according to the disposed methodology. The data were processed using correlation and regression analysis. The main factors for harvesters were known: number of harvested trees per 1 ha, the distance of trees from a skidding trail (working field width), volume of felled trees, frequency of resetting the measuring device in the course of processing 1 tree (increased number in the period of sap), relative site class (branching) and slope. Factors of the time consumption of a forwarder could be more complicated than for a harvester: volume of harvested timber per 1 ha, spacing of skidding trails, mean volume and length of particular assortments, skidding distance etc.*

1. Introduction

In Czech forestry, highly mechanized technologies of forest harvesting based on two groups of machinery are recently increasingly used, viz. harvesters and forwarders. The logging technologies often called "harvester technologies" are used particularly in tending felling. However, they occupy also an important position in main and salvage fellings.

As against traditional logging technologies based predominantly on tree-length logging and using power saws for felling and primary conversion of trees harvester technologies are characterized by several typical properties: they are based on short-length logging, require suitable secondary access to forest stands through skidding trails, their production rate is several times higher, economic parameters after conversion to a produced assortment are favourable, logistic chain is changed of the flow of harvested wood from the forest owner to a customer, occupational safety is increased through the reduction of direct contacts of workers with wood, the technologies are usually environmentally friendly etc. Drawbacks consist in high purchase costs, necessity of the perfect organization of work including the provision of a sufficient amount of wood for logging operations, high requirements for the quality of machine operators as well as limitations given by natural conditions (terrain, tree species etc.).

Economics of the operation of harvester technologies is markedly affected by their production rate. Harvester technologies come from Scandinavian countries with quite different natural conditions as compared with the Czech Republic. Therefore, it is not possible to take over only passively Scandinavian results and extensive experience from the observation of efficiency parameters of harvester technologies. Harvester technologies are, however, successfully used for a number of years also in neighbouring Central-European countries, particularly in Germany and Austria under conditions comparable or even more difficult than those occurring in forests of the Czech Republic. Thus, it is possible to expect further increase in using harvester technologies in logging operations in our country. It is also possible to compare harvester technology parameters achieved in our country and abroad.

2. Problems of the production rate of harvester technologies in logging

Production rate in forest operations is affected by three basic groups of factors: man – machine – natural environment. However, the production rate of harvesters and forwarders need not be related to the same factors.

In the group of factors "man" is, however, evident that in both types of machines the fundamental effect on the production rate represents the person of an operator. Harvesters and forwarders are machines where the proportion of particularly manual labour is reduced, however, operators of the machines have to fulfil some physiological and psychological conditions and to exhibit a sufficient experience (skilled workers). A period necessary to achieve 100% performance is relatively long amounting to as many as 390 working shifts (Simanov, 1998). A human factor is related not only to the direct operation of machines but it is of substantial use in the selection of suitable stands, in the quality of the technological preparation of workplaces including skidding trail marking, landing location, marking of timber for felling operations and at the control of the production process (plan of the machine use, number and time of their transfer, daily use of machines, maintenance and repairs of machines).

The group of factors "machine" is particularly characterized by their construction, i.e. machine type, engine power, reach of a hydraulic boom, construction of a felling head (in harvesters), passability (of the forest) etc. As for forwarders, important factors are the size of a loading capacity, grapple dimensions etc.

The group of factors "natural conditions" is characterized particularly by the type of terrain, microrelief, ground bearing capacity and the occurrence of obstacles. Other factors such as stand characteristics (tree species and species composition, standing volume, methods of management, yield class, felling season etc.) cannot be omitted. As for forwarders, it is necessary to take into account the structure of logs (assortments) produced by a harvester, the quality of their sorting along a skidding trail and a skidding distance. Harvesters can be differentiated according to various criteria particularly for the purpose of quantification of their productivity and specification of fields of recommended use. Engine power appears to be a useful and objective criterion serving for the classification of harvesters into the following three categories (e.g. Forbrig, 2001):

Class 1 – engine power < 70 kW – small harvesters

Class 2 – engine power 70 – 140 kW – medium harvesters

Class 3 – engine power > 140 kW – large harvesters.

The most usual harvesters used at present in the Czech Republic are harvesters of Class 2. The paper is also based on results of research studies aimed at Class 2.

3. Methodical procedures

Time studies of the production rate of harvesters and forwarders in relation to objective conditions of the working environment were worked out for representatives of the group of harvesters suitable for thinning operations – Rottne 2004 of engine power 93 kW and a representative of harvesters with a possibility to use it in stands of larger volumes of felled trees including main felling – Rottne 5005 of engine power 140 kW. Time studies were carried out in forwarders forming production "junctions" with the harvesters, viz. Solid F 9 and Solid F 12. Effects of the machine operator in the study were eliminated in such a way that all observations were carried out in the most experienced operator only (time of training more than 2 years).

Observations in harvesters were carried out in sample plots of a width equal to a width of a working field and length of 25 m situated in such a way a skidding trail to go through the centre of the sample plot. In the sample plot, following parameters were determined: standing volume, slope, felling intensity, stand density and relative yield class. Trees intended for felling were numbered and their distance from the skidding trail centre was recorded. The course of the harvester operation in the sample plot was taken by a video camera. The number of produced assortments, number of produced logs, number of resetting of the measuring device, number of shortening the tree tops, time for gripping the tree and time for processing the tree were determined from video recordings in processing each of the trees. In addition to this, time data were measured and recorded by means of a stopwatch and data from board computers were also used. To determine the production rate of a machine it is generally necessary to know particular stages of its working process. The working cycle of harvesters was divided into several typical operations: gripping the tree including the potential passage of a harvester, felling, delimbing, cross-cutting and sorting. Data were statistically analysed in two groups:

Time for gripping a tree (t_1) - in data processing relationships were looked for between the time and:

- the distance of the tree from the skidding trail
- the number of felled trees per ha
- stand density
- terrain slope.

Time for processing a tree (t_2) - in data processing relationships were looked for between the time and:

- the distance of the tree from the skidding trail
- the number of felled trees per ha
- stand density
- terrain slope
- relative yield class (branchiness)
- the number of produced logs
- the number of produced assortments
- the frequency of resetting the measuring device (evening the butts)
- cross-cutting the logging residues.

Monitoring the time requirements of forwarder operations necessitated division into 3 different stages:

Loading – the forwarder is monitored in the same sample plots as the harvester. A time is determined which is necessary for forwarding the wood from the whole area.

In the majority of cases, the forwarder passes through the area several times gathering another assortment at each of the passages. Out of the sample plots, time of loading the forwarder is monitored, the number and length of loaded logs and covered distance per a load.

Passage into the stand and from the stand – driving velocity, driving time, route length, road surface and slope.

Unloading – time of unloading, determining the number of logs of admixed assortments the operator had to sort out from the main assortment.

The data obtained were then processed using correlation and regression analysis through special statistical programs. The limited scope of the paper does not make possible to give a detailed analysis of determined relationships of time consumption as well as forwarder production rates.

4. Results

The time of a working unit (t) consist of (for each of the trees) a time for passage and grip (t_1), i.e. a time from dropping the slash of a previous tree up to starting the felling of a next tree and a time for processing the tree (t_2). To express the dependence through correlation and regression analysis, consumption of time per 1 tree appears to be more suitable than per 1 m^3 because the latter can be formed by the various number of trees and the number of trees is related to the number of repeating some operations (felling etc.).

$$t = t_1 + t_2 \qquad \text{(s/tree)} \qquad (1)$$

Knowing the average volume of a tree (V_t) we can determine time consumption per 1 m^3 (t_{m3}).

$$t_{m3} = t_c / V_t \qquad (\text{s/m}^3) \qquad (2)$$

In order wee to be able to assess the production rate of a harvester (P) it is necessary to take into account not only the time of the unit of work but also the time of necessary breaks and the time of a batch job. Research results show that the time of a working unit does not exceed (in this type of a machine) 45 minutes within an hour. Production rate is determined according to a formula as follows:

$$P = (60 * t_w) / t_m \qquad (\text{m}^3/\text{h}) \qquad (3)$$

t_w – time of a net work of a machine within an hour (min), t_{m3} – time for processing 1 m^3 (s)

or:

$$P = V_t * k * 60 / (t_1 + t_2) \qquad (\text{m}^3/\text{h}) \qquad (4)$$

Based on the statistical analysis of data, equations have been compiled for Norway spruce to express a time for passage and grip (t_1) and a time for processing a tree (t_2) which are as follows:

4.1 Rottne 2004 harvester

$t_1 = (22.3 + 1.2 * d - 0.0164 * n) * (1 + 0.0034 * sl^2)$ (s/tree) (5)

d – distance of a tree from the skidding trail (m), n – number of felled trees per 1 ha, sl –slope (°)

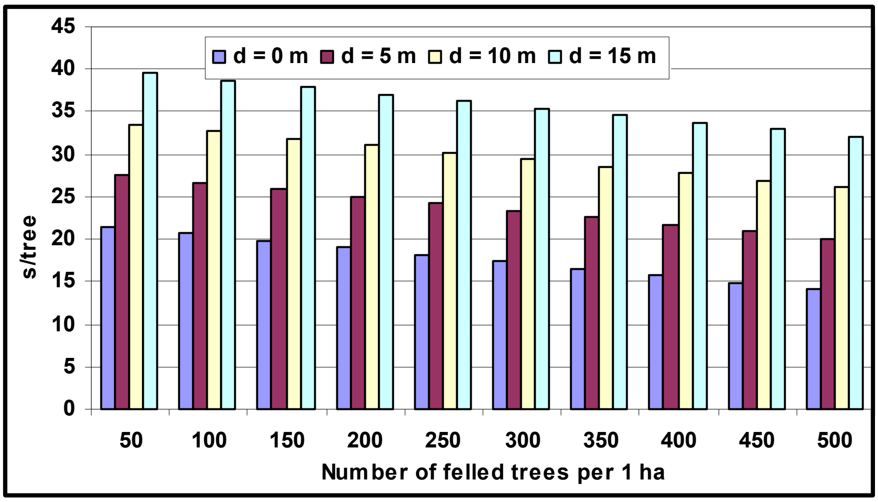

Figure 1: Time t_1 necessary for the passage and grip of a tree in R 2004 harvester

The consumption of work logically increases with the distance of a tree from a skidding trail when the operator is obliged to reach to a greater distance into the stand or to run in out of the trail in trees of a greater volume and the harvester boom does not have sufficient force available for handling a tree. On the other hand, the greater number of felled trees decreases time consumption. Under the situation, the operator is able to process more trees from one position, the machine passage requires less time and due to the thinner stand the movement of the machine and its boom is facilitated. The basic time is increased with the increasing slope of the terrain but not proportionally because from a certain limit the harvester operation on a slope is not possible at all whereas slopes < 5° show relatively small effects.

$t_2 = (60.4 * V_t^{0.495} * (1 + 0.1 * r) + 3.6 * nr) * (1 + 0.0029 * sl^2)$ (s/tree) (6)

V_t – volume of a felled tree (m^3), r – relative yield class, nr – number of resetting the measuring device, sl - slope (°)

The time is related above all to the volume of a particular tree and branchiness (relative yield class). Necessity to reset the measuring device under incorrect reading the log length due to slipping the measuring wheel (at catching stripped bark on its points) can be considered as a time allowance irrespective of the tree volume. Slope multiplies again the time consumption for particular operations. In addition to the machine stability it also effects stacking the assortment when the operator is obliged to stack assortments in such a way to prevent their movement downhill.

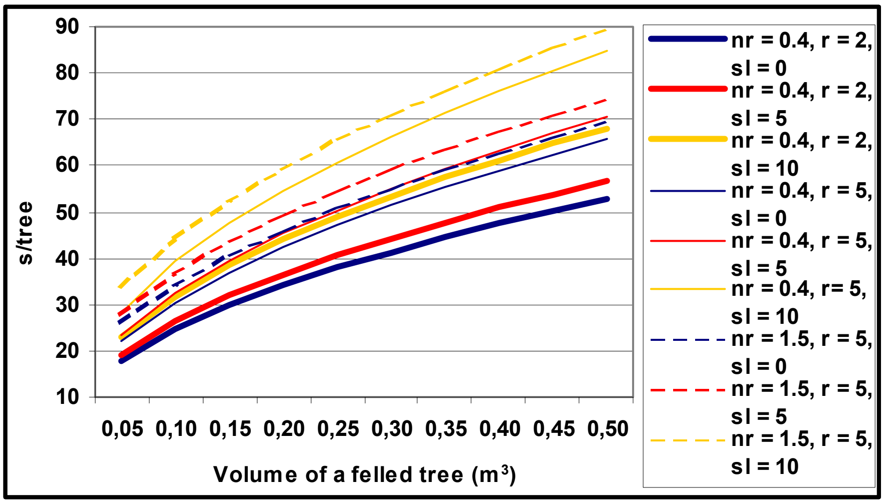

Figure 2: Time t_2 necessary to process a tree by R 2004 harvester in relation to the frequency of resetting the measuring device (nr), relative yield class (r) and slope (sl)

4.2 Rottne 5005 harvester

$t_1 = (25.4 + 2.35 * d - 0.027 * n) * (1 + 0.0076 * sl^2)$ (s/tree) (7)

d – distance of a tree from the skidding trail (m), n – number of felled trees per 1 ha, sl – slope (°)

Time t_1 in R 5005 harvester is affected by the same factors as in R 2004 harvester. Only parameters in particular quantities are different.

$t_2 = (62.6 * V_t^{0.45} + 4{,}2\ nr) * (1 + 0.0083 * sl^2)$ (s/tree) (8)

V_t – volume of a felled tree (m^3), nr – number of resetting the measuring device, sl – slope (°)

An equation to determine the time for processing a tree is structurally simpler which is probably affected by small variability of stands where the study was carried out.

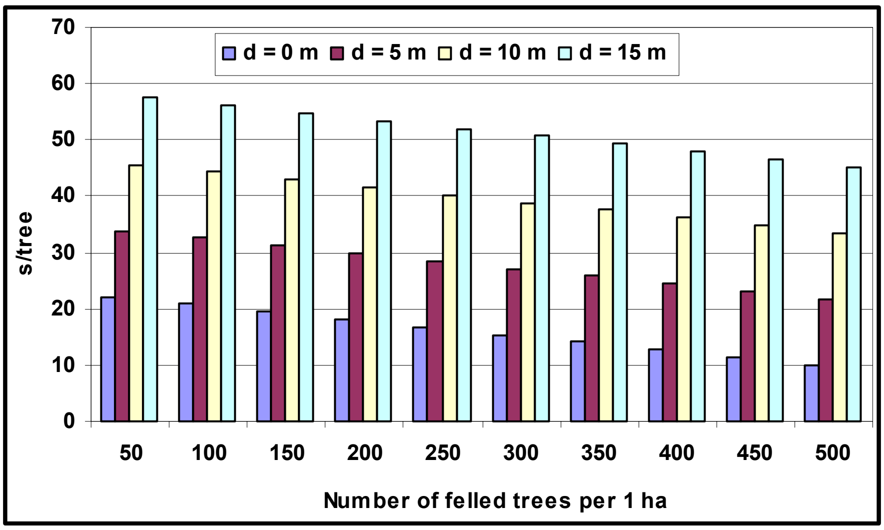

Figure 3: Time t_1 necessary for the passage and grip of a tree in u R 5005 harvester

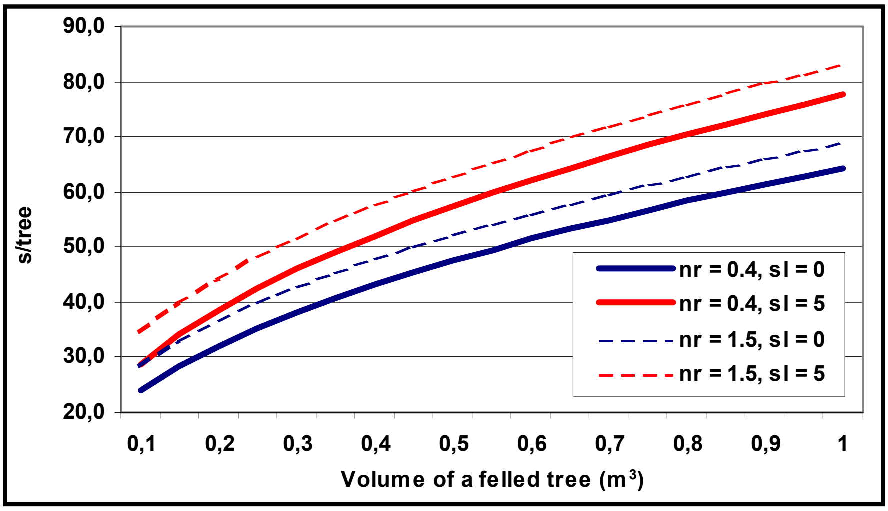

Figure 4: Time t_2 necessary to process a tree by R 2004 harvester in relation to the frequency of resetting the measuring device (nr) and slope (sl) at relative yield class 3 - 4

Equations expressing consumption of time t_1 and t_2 were applied for determining relationships of the harvester production rate as depicted in Figures 5 to 8. An example of the production rate of R 2004 harvester in relation to the terrain slope determined according to the procedure mentioned above is given in Figure 5.

In addition to the slope inclination the harvester production rate is markedly affected by branchiness - relative yield class (Figure 6). On the other hand, relatively small effects of felling intensity can be caused by small dimensions of the machine and its good manoeuvrability or by the character of stands where the study was carried out.

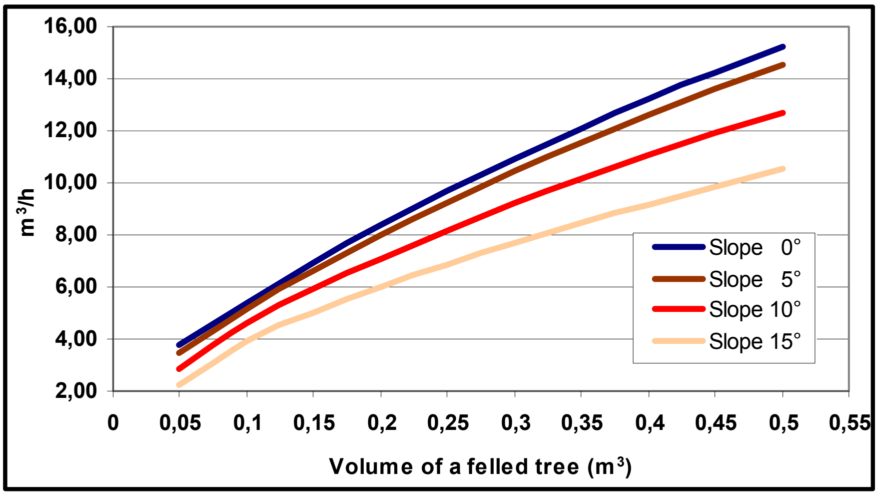

Figure 5: The course of the production rate of R 2004 harvester in relation to the slope inclination
(felling intensity - 40 m³/ha, skidding trail spacing - 20 m, relative yield class – 4, frequency of resetting the measuring device – 0,4, time of a net work of a machine within an hour – 45 min).

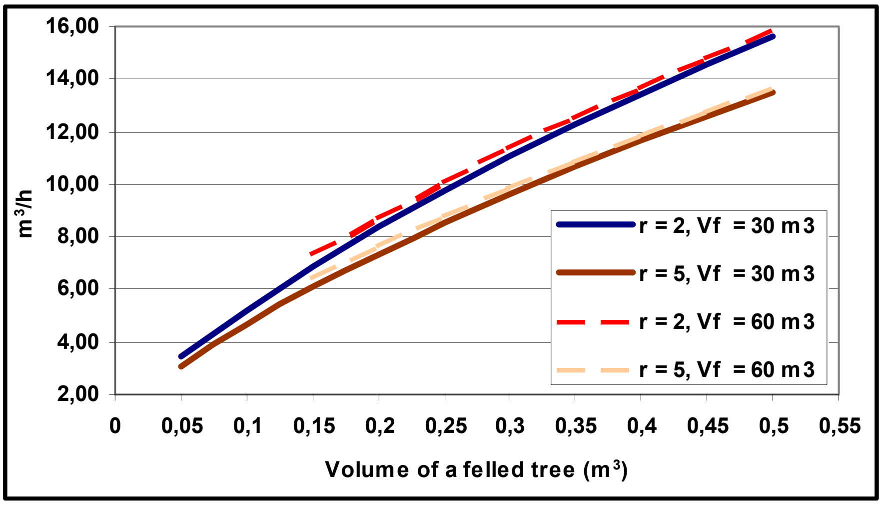

Figure 6: The course of the production rate of R 2004 harvester in relation to relative yield class (r) and felling intensity – volume felled per 1 ha (Vf) *(slope – 5°, skidding trail spacing - 20 m, frequency of resetting the measuring device – 0,4, time of a net work of a machine within an hour – 45 min).*

Slope inclination manifested itself particularly in R 5005 harvester (Figure 7). The cause of the fact can consist in the insufficient variability of slopes in sample plots which cam be the reason of overlaying the factor by another factor (actual capability of the machine operator etc.). Effects of the intensity of felling were very marked. Figure 7 shows that the higher intensity of felling considerably increases the harvester production rate. Felling in the time of sap resulting in more frequent resetting of the measuring device within processing 1 tree appears to be a marked factor decreasing the harvester production rate. According to experience obtained under realistic actual conditions, skidding trail spacing is of much greater importance than indicated by model equations (see Figure 8). Within the study, only 1 plot occurred where the spacing of skidding trails was about 30 m and, therefore, it was not possible to obtain data with a sufficient variability.

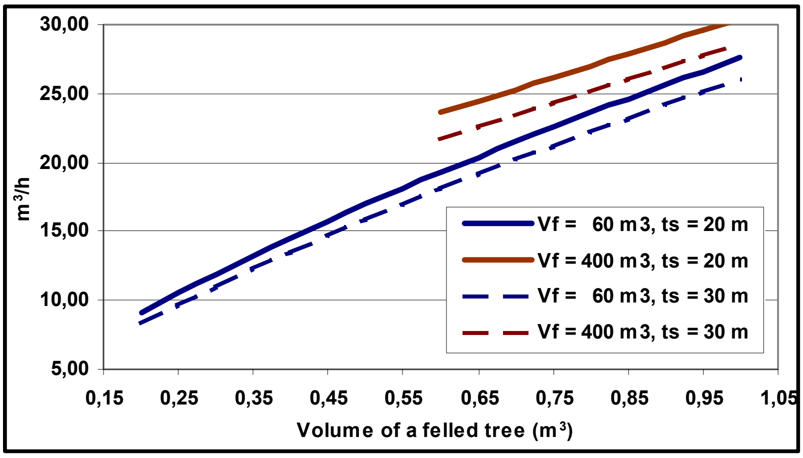

Figure 7: The course of the production rate of R 5005 harvester in relation to the skidding trail spacing (ts), felling intensity – volume felled per 1 ha (t) and the frequency of resetting the measuring device *(slope – 0°, relative yield class – 3 – 4, frequency of resetting the measuring device – 0,4, time of a net work of a machine within an hour – 45 min).*

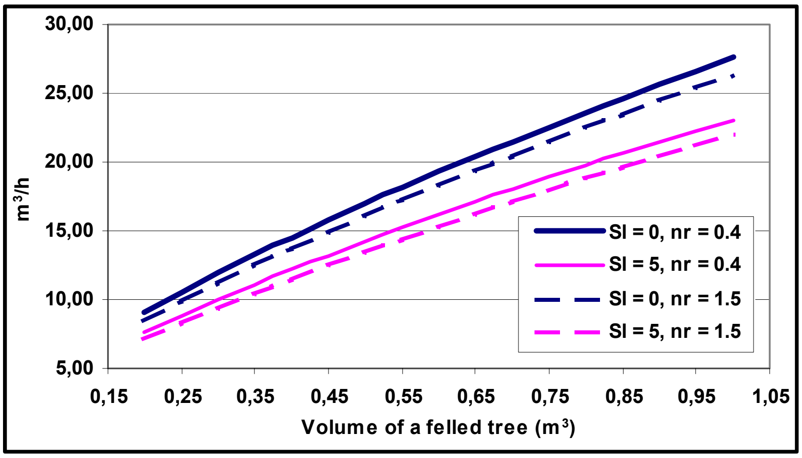

Figure 8: The production rate of R 5005 harvester in relation to the frequency of resetting the measuring device (nr) and slope inclination (sl) *(felling intensity - 60 m^3/ha, skidding trail spacing - 20 m, relative yield class – 4, time of a net work of a machine within an hour – 45 min).*

5. Discussion

In determining time consumption and production rate of harvesters models were treated separately for each of the two operation phases (processing the tree, gripping the tree and machine passage). Factors affecting the production rate of harvesters agree with other authors who also mention the machine type, stem volume, volume felled and slope inclination.

With the increasing volume of the stem time for its processing slightly increases, however, production rate per m^3 markedly increases. Growth in the production rate decreases with the approaching limit of the technological use of the machine as mentioned e.g. by Forbig (2001). The fact is of considerable importance in the selection of stands by the company management. If the considerable proportion of trees occurs with parameters near the upper limit of the harvester usability, a marked decrease in production rate and increase in costs appear among others in connection with the increase in repairs of an overloaded machine. Thus, it is not suitable to buy machines of lower power categories which are less expensive, however, they are intended for operations in stands of smaller stem volumes (particularly in thinnings) and then to apply them in main fellings where stem volumes exceed parameters of the machines. Similarly, opposite approach is not also effective, i.e. to apply machines of higher power categories into stands of lower dimensions of trees (thinnings) because capacities of the machines will not be fully used.

Felling intensity (volume felled) affects inversely proportionally particularly time consumption for the machine passage and grip of a tree t_1 which (in an extreme case) can result in the predominance of time t_1 over t_2. (time for processing the tree). Similar effects can be also shown by the excessive width of a workspace because if the harvester is obliged to drive in the stand from a skidding trail and to skid (draw) trees to the trail it means an increase in the total time per a tree.

In our studies, slope inclination proved to be a distinct factor, however, the study was not carried out in a sufficiently broad range of slopes (in our country, harvester technologies are not applied in steep terrain for the present). If we use division of the terrain slope according to Stampfer (2001) our measurements were carried out under conditions of gentle slopes (< 25%). In the category of slopes there is their effect on the consumption of a working time of a harvester.

Effects o the tree volume are not too important for the number of logs produced (assortments). A thin and low tree serves for the production of short logs, a large-diameter and tall tree provides even several longer assortments and the total number of logs in both trees is in principle balanced. For example, from a tree of a volume of 0.10 m^3 8 two-metre logs can be produced while from a tree of 1.00 m^3 it is possible to produce 2 four-metre, 4 three-metre and 3 two-metre logs.

If we compare the production rate of the studied Rottne 5005 harvester with data of Forbrig (2001) who gives for the comparable power category of harvesters 140 kW average production rate 11.30 m^3 and 45 trees per motor/hour (mth) at the stem volume of 0.25 m^3 we can find that the average production rate of R 5005 harvester reached comparable values at the same stem volume because a minimum production rate ranged about 11.5 m^3. However, if we introduce also the parameter of felling intensity into the calculation then R 5005 reached a production rate higher by about 1.9 m^3 as against converted data by Forbrig (2001). For example, Pausch (in Ulrich et al., 2002) gives at the same stem volume production rate of 11.8 m^3/mth. Stampfer (2001) gives following production rates for machines with similar engine power: Impex Koenigstiger harvester 13.65 m^3/mth at 25% slope, Valmet 911 Snake 15-16 m^3/mth at 25% slope etc. Nordansjö (2001) gives an average production rate of harvesters in Sweden 10 m^3 per hour in thinnings and 20 m^3 in main fellings.

Similarly, if we compare the production rate of our Rottne 2004 harvester amounting to 7.37 to 12.7 m^3 /hour at the average stem volume of 0.15 m^3 in relation to the intensity of felling with data by Forbrig (2001) who gives production rate of 7.3 m^3/hour at 0.15 m^3 stem volume we can find that the production rate of both machines is almost comparable. Thus, the production rate of harvesters reached under Czech conditions is comparable with a level reached in other countries.

The higher production rate of harvesters in main fellings as against thinnings is evident and is related particularly to the reduction of time t_1 for passage and grip of the machine. Within thinnings, also Stampfer (2001) confirms that with the increasing intensity of felling (and thus volume felled) time for passage decreases and the harvester production rate increases. Our results concerning the relationship between the production rate and felling intensity are not identical with those by Stampfer who dealt with a caterpillar harvester at 20% slope, however, their trend is similar.

It is remarkable that performance standards for forwarders and harvesters used at present in the Czech Republic set for forwarders much greater performance rates than for harvesters. Results of our studies, however, show the opposite.

6. Conclusion

The research studies demonstrated various effects of external and internal factors on the consumption of working time and thus also on the production rate in harvesters of a medium power category up to 140 kW and of adequate forwarders. The findings presented are supported by a number of field measurements and statistic calculations. However, with respect to various natural conditions in Czech forestry they do not involve all their variants which could occur particularly as for higher values of slope inclination. Nevertheless, it is possible to make conclusions utilizable in forest practice. If the harvester technology is to fulfil all requirements it has to be applied under conditions corresponding to parameters and possibilities of the machines. If the principle is taken into consideration in using the harvester technologies it is possible to expect increase in labour productivity as against motor/manual methods of logging predominating so far.

7. Note

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