EFFECT OF INDIVIDUAL TREE VOLUME ON OPERATIONAL PERFORMANCE OF *HARVESTER* PROCESSOR

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Abstract

The need to obtain multi-products from the forest makes the wood processing an important step in the timber harvest, being necessary, then, to understand the influence of the stand characteristics on the operational performance of the machines. The aim of this study was to evaluate the effect of the individual tree volume on the operational performance of the harvester forest processor in *Pinus taeda* L. stands, in order to assist in planning operations and reducing production costs. The analyzes were carried out by means of a time and motion study, determining the time consumed in the phases of the operational cycle, mechanical availability, operational efficiency, productivity, and production costs in three stands with different individual mean volumes (IMV): I (1.21 m^3 $tree^{-1}$); II (1.34 m^3 $tree^{-1}$) and III (1.61 m^3 $tree^{-1}$). In a completely randomized design, the averages of the variables were compared, as well as models for estimating productivity and production costs were fitted according to individual tree volume. The results showed that the processing element consumed a significant part of the total operational cycle time, with 46, 53 and 64% in treatments I, II and III, respectively, with an average operational efficiency of 56% in all treatments. Productivity increase and reduction of production costs were observed in the order of 43 and 30%, respectively, with the increase in IMV from 1.21 to 1.61 m^3 $tree^{-1}$. Such behavior can be represented by the third degree polynomial, which demonstrated the operational limit of 1.5 m^3 $tree^{-1}$ for the harvester forest processor.
Keywords: forest harvesting; forest processor; planning.

Resumo

Efeito do volume individual de árvores no desempenho operacional do processador harvester. A necessidade da obtenção de multiprodutos da floresta faz com que o processamento da madeira seja uma etapa importante da colheita da madeira, sendo necessário entender a influência das características do povoamento no rendimento operacional das máquinas. Objetivou-se avaliar o efeito do volume individual das árvores no rendimento operacional do processador florestal *harvester* em povoamentos de *Pinus taeda* L., de modo a auxiliar o planejamento das operações e a redução dos custos de produção. As análises foram realizadas por meio de um estudo de tempos e movimentos, determinando os tempos consumidos nas fases do ciclo operacional, a disponibilidade mecânica, a eficiência operacional, a produtividade e os custos de produção em três povoamentos com diferentes volumes médios individuais (VMI): I (1,21 m^3 $árv^{-1}$); II (1,34 m^3 $árv^{-1}$) e III (1,61 m^3 $árv^{-1}$). Em um delineamento inteiramente casualisado, comparou-se as médias das variáveis, bem como ajustou-se modelos para estimativa da produtividade e dos custos de produção em função do volume individual das árvores. Os resultados mostraram que o elemento processamento consumiu parte significativa do tempo total do ciclo operacional com 46, 53 e 64% nos tratamentos I, II e III, respectivamente, com eficiência operacional média de 56% em todos os tratamentos. Foi observado um aumento de produtividade e redução de custos de produção na ordem de 43 e 30%, respectivamente, com o aumento do VMI de 1,21 para 1,61 m^3 $árv^{-1}$. Tal comportamento pode ser representado por meio do polinômio do terceiro grau, que demonstrou o limite operacional de 1,5 m^3 $árv^{-1}$ para o processador florestal *harvester*.
Palavras-chave: colheita florestal; processador florestal; planejamento.

INTRODUCTION

Processing is an important activity in the harvesting of wood, characterized by the measurement, dewatering and tracing of the shaft in logs of different dimensions specified by the consumer unit (SANT'ANNA, 2014). This activity can be performed by manual, semi-mechanized or mechanized methods, and when machined, the wood processing is usually performed using *harvester*, which refers to a machine composed of a crane and a saber head, capable of producing logs with different assortments (MACHADO *et al*., 2014).

Wood processing is the last step of the whole tree harvesting system, being an activity carried out on the edge of the field, after cutting and extracting trees (ROBERT, 2012). The use of *harvester* in the processing of wood is due to the need of precision in log sizing, being utilized by companies that produce multiproducts of the stands to serve the wood consumer market (MURPHY, 2003; STRANDGARD, 2009).

According to Robert (2012), the activities carried out by *harvester* differ in the wood harvesting system employed. In the short log system, the *harvester* performs the cutting of trees in the stands within the field, carrying out the logging, processing and pre-extraction of the wood (stacking) (SANT'ANNA, 2014). However, in the entire tree system, *harvester* only performs the wood processing at the edge of the field with low displacement during the operational cycle.

In addition, because individual tree processing occurs, the individual mean volume (IMV) of the trees becomes the most influential variable in the operating efficiency of the *harvester* processor (MALINOVSKI *et al.*, 2006; SILVA *et al*., 2010). Several works, such as Leite *et al*. (2013), Seixas and Batista (2014) and Simões *et al.* (2014), evaluated the yield of *harvester* in the cut to length system cutting activity, however, the lack of studies of this machine in the wood processing of the whole tree system stands out, especially in conditions of forest management for multiple use, considering that the *harvester* only performs the wood processing operation, but, producing several assortments.

In this context, the aim of this study is to evaluate the effect of individual tree volume on the operational performance of the forest processor *harvester* in a whole tree system, in order to subsidize the operations planning, the increase of productivity and the reduction of production costs, taking into account the hypothesis that the increase of IMV entails higher machine operating efficiency.

MATERIAL AND METHODS

The study was carried out in a forest company located in the North region of the state of Santa Catarina, Brazil, between the coordinates 26º42'52" S and 49º29'00" W and average altitude of 530 m. The climate of the study region is classified as Cfb, according to Köppen, being mesothermal humid, without a definite dry season and with hot summers and rigorous winters, being the annual average temperature of 19.7 ºC and the annual precipitation varying between 1,600 to 1,700 mm. The ground had been classified as typical Humic Cambisol of sandy clay loam texture and typical Humic Entisol of sandy clay loam texture with plain to softly wavy relief (SAMPIETRO; LOPES, 2011).

Three standings of *Pinus taeda* L. with different IMV of the trees (I, II and III) (Table 1) were evaluated, which were previously managed with thinning, aiming the production of multiple uses for wood in the final cut.

Tabela 1. Características dos povoamentos avaliados de *Pinus taeda*.
Table 1. Characteristics of evaluated *Pinus taeda* stands.

Characteristics	**IMV I**	**IMV II**	**IMV III**
IMV (m^3 $tree^{-1}$)	1.21	1.34	1.61
Age of cut (years)	24	39	39
Basal area ($m^2 ha^{-1}$)	29.05	44.36	45.36
Number of trees (n ha^{-1})	333	410	416
Mean DBH (cm)	34.62	36.57	36.45
Average height (m)	28.34	29.52	29.45
V (m3 ha-1)	403.0	550.0	670.0
Ground declivity (%)	7.0	8.0	8.0

In which: IMV = individual mean volume; n = number; DBH = diameter at breast height (1.30 m from the ground); and V = settlement volume.

The evaluated system of wooden harvest was of entire trees (*full tree*), where the *feller buncher* carried out the cut and the piling up of the trees in beams disposed in the interior of the field; the *skidder* that carried out the pull of trees to the edge of the field; and the *harvester* forest processor that it carried out the delimber, top cutting and tracing of the wood, piling up the logs in the edges of the field.

The *harvester* processor evaluated was composed by a base machine with normal rated power of 103 kW, twirled of mats and operating weight of 21.0 Mg. The head had a weight of 1,218 kg, maximum cutting diameter of 0.75 m and was equipped with four dismantling knives. In all situations evaluated, to avoid problems with bias, the same operator was observed in the same work shift.

The operational performance analysis was executed through a time and motion study to determine the operating cycle times, the mechanical availability, the operational efficiency and the productivity of the machine. It was used the continuous time timing method with the use of centesimal timer and specific forms. The approach used, according to Magagnotti and Spinelli (2012), was an experimental study and modeling, where input factors should be measurable and preferably continuous, meaning that they are quantitative and within an interval where any number can exist.

The sampling was defined according to the methodology proposed by Murphy (2005), through a pilot study, obtaining the minimum number of observations of the operational cycle of the machine, in order to reach the maximum permissible error of 5%, according to equation (1):

$$n = \frac{t^2 \times Var(WCT)}{\left(E \times \frac{\overline{WCT}}{100}\right)^2} \quad (1)$$

In which: n = minimum number of observations required; t = value of t for the 95% probability level; Var = variance of the duty cycle time; E = maximum permissible error limit of 5%; and WCT = average time of work cycles (minutes).

For the time and motion study, the operating cycle of the *harvester* processor was divided into the following partial elements: 1) Search and Processing, characterized by the time consumed in the search and processing of the trees; 2) Displacement, characterized by the time consumed in the motion of the machine during processing; and 3) Interruptions, referring to machine downtime for various reasons.

The mechanical availability, defined by the working time in which the machine was mechanically able to perform productive work in relation to the programmed time, disregarding the times in preventive and/or corrective maintenance, being obtained by equation (2):

$$MA = \frac{TP\text{-}TM}{TP} \times 100 \quad (2)$$

In which: MA = mechanical availability (%); TP = time programmed for the work (hours); and TM = time in preventive and corrective maintenance (hours).

The operational efficiency was calculated as the percentage of working time in which the machine operated effectively, disregarding the operational and non-operational interruption times, as presented in equation (3):

$$OE = \frac{ET}{TP} \times 100 \quad (3)$$

In which: OE = operating efficiency (%); ET = effective working time (hours); and TP = time programmed for the work (hours).

Productivity was determined by multiplying the individual mean volume of trees by the number of trees processed, divided by the hours actually worked, according to equation (4):

$$PR = \frac{N \times IMV}{WH} \quad (4)$$

In which: PR = productivity (m^3 and he^{-1}); N = number of trees processed; IMV = individual mean volume of trees (m^3); and WH = working hour (hour).

The cost analysis was performed based on the determination of operating and production costs. Operating cost was determined by the accounting method, in accordance with the methodology proposed by Miyata (1980), using measured and estimated values. Operating costs included fixed costs (depreciation, interest and insurance), variable costs (fuels, lubricants and greases, hydraulic oil, conveyors, maintenance and repair and transport of personnel), personnel costs (salaries and social charges), and the cost of administration. The cost of production was calculated by equation (5):

$$CP = \frac{OC}{PR} \quad (5)$$

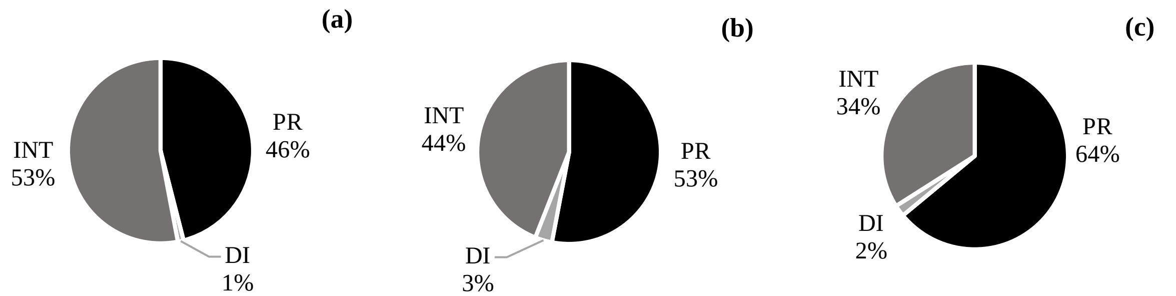
In which: CP = cost of production (R\$ m^{-3}); OC = operating cost (R\$ h^{-1}); and PR = productivity (m^3 h^{-1}).

Using a completely randomized design, three treatments (IMV) and different numbers of repetitions (operating cycles) were considered, being the study performed by a single operator on a single machine. The meteorological characteristics at the time of the study were homogeneous. The mean values of the elements of the operational cycle and the yields of the *harvester* forest processor were subjected to the Kolmogorov-Smirnov normality test, to the homogeneity test of the Bartlett variances and, when significative by the F test, the means were compared by the Tukey test at the 5% error probability level. Statistical analyzes were performed with the assistance of the statistical software ASSISTAT beta version 7.6.

In addition, the adjustment of regression models was performed to verify the relationship between the dependent variables "productivity" and "production costs" and the independent "individual tree volume". The models tested were: exponential, linear, logarithmic, polynomial of second and third degree and power. At the end, the best fitted model was presented, evaluated by means of the coefficient of determination (R^2) presented in a graph with the actual and estimated values.

RESULTS

The numbers of operational cycles of *harvester* forest processor were 999, 1,230 and 1,248 for IMV treatments I, II and III, respectively, requiring 273, 926 and 1,005 operating cycles to reach the maximum permissible error of 5%. Figure 1 shows the percentage shares of the operational cycle elements of forest processor *harvester* in stands of *Pinus taeda* with IMV I (1.21 m^3 $tree^{-1}$); II (1.34 m^3 $tree^{-1}$) and III (1.61 m^3 $tree^{-1}$).

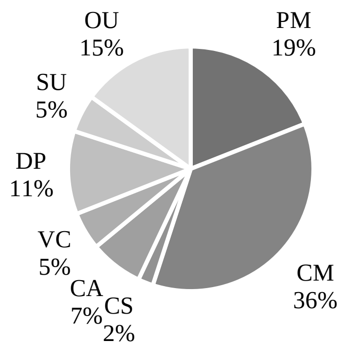


In which: PR = processing; DI = displacement; and INT = interrupts.

Figura 1. Percentuais dos elementos do ciclo operacional do processador florestal *harvester* nos povoamentos de *Pinus taeda* com VMI I (a); VMI II (b); e VMI III (c).

Figure 1. Percentages of the operational cycle elements of the harvester forest processor in *Pinus taeda* stands with IMV I (a); IMV II (b); and IMV III (c).

The processing was the partial element that consumed the highest total time of the operational cycle, with 46, 53 and 64% in the stands with IMVs I, II and III, respectively. It was noticed that there was a percentage increase of the processing time of the trees with the increase of the IMV. The causes of the high time consumed with interruptions are presented in Figure 2.



In which: PM = preventive maintenance; CM = corrective maintenance; CS = change of shift; CA = change and adjustment of cutting; VC = verification of cut-off measurements; DP = displacement of processing local change; SU = supply; and OU = others.

Figura 2. Percentage of the causes of the operational interruptions of the forest processor *to harvester* in povoamentos of *Pinus taeda* with VMI I, II and III.

Figure 2. Percentage of causes of the operational interruptions of the harvester forest processor in *Pinus taeda* stands with IMV I, II, and III.

Table 2 shows the times in minutes of the partial elements of the operating cycle of the *harvester.* In the partial search and processing element, an average of 1.2 minutes was consumed, with no statistically significant difference between the studied stands. However, the times consumed with displacement were influenced by the volume of the bundles of trees arranged in the margin of the field, and it was possible to verify the shorter time consumed in the IMV III stand.

Tabela 2. Tempos médios do ciclo operacional do processador florestal *harvester* em povoamentos de *Pinus taeda* com VMI I, II e III.
Table 2. Average times of the operational cycle of the harvester forest processor in *Pinus taeda* stands with IMV I, II, and III.

IMV	**Average cycle time (minutes)**		
	Search and Processing	**Displacement**	**Total**
I	1.16 ± 0.69	0.74 ab ± 0.57	1.90
II	1.21 ± 0.56	1.04 a ± 0.66	2.25
III	1.25 ± 0.57	0.57 b ± 0.59	1.82
Average	**1.20**	**0.78**	**1.99**

In which: IMV = individual mean volume; and averages followed by the same letter in the column do not differ statistically by the Tukey test at the 5% level of error probability.

The average mechanical availability of the machine was 84%, while the operational efficiency was 56% (Table 3). The average productivity per working hour of the *harvester* forest processor varied from 62.8 to 89.8 m^3 per effective hour of work, therefore, there is an increase in the machine's efficiency around 43% when the IMV increased from 1.21 to 1.61 $m^3 tree^{-1}$, being verified absence of significant statistical difference in IMV II and III stands by the Tukey test at the level of 5% of probability of error.

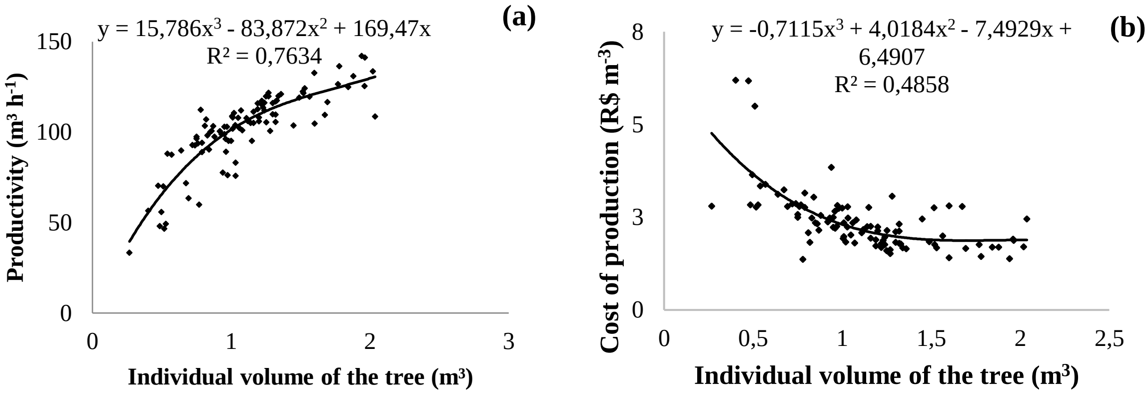
Tabela 3. Produtividade e custos de produção do processador florestal *harvester* em povoamentos de *Pinus taeda* com VMI I, II e III.
Table 3. Productivity and production costs of the harvester forest processor in *Pinus taeda* stands with IMV I, II and III.

IMV	**MA (%)**	**OE (%)**	**PR (m^3 h^{-1})**	**OC (R$ h^{-1})**	**CP (R$ m^{-3})**
I			62.8 a		6.36
II	84	56	80.5 b	224.03	4.96
III			89.8 b		4.44
Average	84	56	**77.7**	**224.03**	**5.25**

In which: IMV = individual mean volume; MA = mechanical availability. OE = operational efficiency; PR = productivity; OC = operating costs; CP = costs of production; and averages followed by the same letter in the column are not statistically different by the Tukey test at the 5% error probability level.

The average operating cost of the machine was R$ 224.03 per effective hour of work, and it can be noted that, as the average individual volumes of the trees increased, the cost of production values reduced by around 30% between IMV I to III. Therefore, this result showed the effect of tree volume on the operating efficiency of the *harvester.*

In Figure 3, the effect of tree volume on *harvester* productivity is observed. The third degree polynomial was adequate to estimate the productivity and production costs as a function of the individual trees volume with determination coefficients of 0.76 and 0.49, respectively. The lowest coefficient of determination in the model to estimate production costs is due to the greater variability of the data in the lower volume values of the trees.



In which: PR = productivity; CP = cost of production; iv = individual volume of the tree; and R^2 = coefficient of determination.
Figura 3. Valores de produtividade (a) e custos de produção (b) em função do volume individual das árvores.
Figure 3. Productivity values (a) and production costs (b) as a function of the individual tree volume.

DISCUSSION

The percentage participation of the partial elements of the operational cycle of the *harvester* processor was represented predominantly by the search and processing element of the trees, with insignificant participation of the displacement element. This is a feature evidenced in the whole tree processing operation that differs from the work done with *harvester* in the short log system by Simões and Fenner (2010) and Robert *et al.* (2013), in which these authors observed a longer time consumed with displacement. In addition, the time spent with the machine displacement was directly related to the volume of the bundle of trees deposited by the *skidder* on the edge of the field, where it was possible to note that the higher the IMV of the stand, the greater the volume of the bundles of trees and less the need of displacement of the machine.

Regarding the operational and non-operational interruptions, it can be stated that they consumed a high time programmed for the work, resulting in operational efficiency of the machine below the values acceptable by forest companies, which vary between 70 and 80%. The main causes of the interruptions were corrective and preventive maintenance, which consumed 36 and 19% of the total operational interruption time and high useful life of the machine in this study. Therefore, in order to increase the operational efficiency of the wood harvesting machines, it is necessary to use an efficient piece replacement logistics, aiming to reduce machine's downtime, as recommended by Linhares *et al.* (2012).

Another cause of the low operational efficiency was the need for interruptions caused by machine displacement (DP), caused by changes in the processing site, in order to allow the *skidder* to deposit new bundles of trees. This result showed the existence of operational planning failures, thus, it is necessary to use larger cutting fronts as a way to mitigate interruptions and increase operational efficiency, avoiding the bottleneck of the operations on the banks of the plots.

Spinelli and Visser (2008), in a study conducted with data from 34 situations of operation studies with *harvester*, found that most interruptions registered were caused by delays lasting less than 15 minutes, which on average corresponded to 60% of all the time in interruptions. However, the authors point out that the times in interruptions varied significantly according to the type of machine used, soil and relief conditions, as well as forest conditions, operator training and operations management. Therefore, it is clear that assessing the causes of interruptions in forest operations is of great importance, since it allows the generation of data to guide administrative decisions, helping to define operational performance targets in order to optimize harvesting systems.

In relation to the productivity of the operation, several other studies with harvester report that this is influenced by several factors, being the main the characteristics of the machine, operator experience, shape and size of the trees, length and number of assortments produced (MALINOVSKI *et al.*, 2006; SPINELLI *et al.*, 2010; HIESL; BENJAMIN, 2013; MAGAGNOTTI *et al.*, 2017).

In the present study, the effect of the individual tree volume on productivity and, consequently, on the production costs of *harvester* was statistically significant. The higher the IMV of the stand, the machine's productivity tended to be higher, because as shown in Table 2, the average cycle time to process trees of lower IMV was not statistically lower than the cycle time to process larger trees IMV. However, it was observed that the productivity increased with the increase of the individual volume of the trees until the maximum volume of 1.5 m^3

per tree, and after this value, there was a decrease of the productivity increase, fact that can be associated to the operational limit of the machine (Figure 3).

In general, the results demonstrate the importance of analyzing factors influencing the operational performance in the harvesting of wood, since they directly interfere in the costs of production and, therefore, in the budget planning of the operations, as well as in the resource dimensioning materials and humans.

CONCLUSIONS

- The element search and processing consumed most of the effective time of the forest processor's operational cycle *harvester* independent of the individual tree volume;
- The individual mean volume of the tree influenced the operational efficiency of the *harvester*, being that the larger the tree volume, the greater the productivity of the machine with consequent reduction of the cost of production;
- The third-degree polynomial model makes it possible to estimate machine productivity and production costs, and it is able to demonstrate the operational limit of the forest processor *harvester*; and
- The volume of the tree is an important variable of the stand to be considered in the planning of the wood processing operation to obtain multiproducts.

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