INCORPORATION OF UNCERTAINTY IN TECHNICAL AND ECONOMIC ANALYSIS OF A FELLER-BUNCHER

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Abstract

The constant technical and economic analysis of timber harvesting operations is essential and determining, due to the monetary magnitude. Traditionally, these analyses are conducted deterministically, which does not allow obtaining values with probabilities of occurrence. Considering this issue, stochastic models were built in order to analyze the behavior of probabilistic production cost in felling operations with feller-buncher, through the Monte Carlo method. The study was conducted in the Central-West region of the state of São Paulo in a forest of *Eucalyptus* sp., with six years of age, planted in 3 x 2 m spacing. Technical analysis was based on the study of time and movements, which determined the effective productivity and economy in the hourly operating cost of the feller-buncher and in the production costs of the operation. Due to uncertainties, probability distributions were assigned to these results, which identified the most relevant variables and quantified the probabilities of the production cost. The results demonstrated that the fuel cost had a statistically significant strong positive correlation coefficient (ρ_s= 0.91) (p-value < 0.01). The hourly cost, consequently, was directly proportional to the production cost of the operation. The production cost of the operation in flat relief was 18% lower than the production cost of the operation in undulating relief.
Keywords: Harvest, time and movements, productivity, operational risk, cost.

Resumo

Incorporação da incerteza na análise técnica e econômica de um feller buncher. A constante análise técnica e econômica das operações de colheita florestal possui caráter essencial e determinante, devido à magnitude dos valores monetários. Tradicionalmente, essas análises são realizadas de forma determinística, o que não permite a obtenção de valores com probabilidades de ocorrência. Nesse sentido, foram construídos modelos estocásticos para analisar o comportamento do custo probabilístico de produção na operação de derrubada com *feller buncher*, por meio do método de Monte Carlo. O estudo foi conduzido na região Centro-Oeste do estado de São Paulo em uma floresta de *Eucalyptus* sp. com seis anos de idade, plantada em espaçamento de 3 x 2 m. A análise técnica foi pautada no estudo de tempos e movimentos, determinando-se a produtividade efetiva e a econômica no custo operacional horário do *feller buncher* e nos custos de produção da operação. Por conterem incertezas, a esses resultados, foram atribuídas distribuições de probabilidade, que permitiram identificar as variáveis mais relevantes e quantificar as probabilidades do custo de produção. Constatou-se que o custo com combustível possui coeficiente de correlação positiva forte (ρ_s = 0,91), estatisticamente significativo (valor p < 0,01). O custo horário, por consequência, foi diretamente proporcional ao custo de produção da operação. O custo de produção da operação em relevo plano foi 18% inferior ao custo de produção da operação em relevo ondulado.
Palavras-chaves: Colheita, tempos e movimentos, produtividade, risco operacional, custos.

INTRODUCTION

In the economic context, the required equipment for mechanized timber harvesting are considered constant inputs. Moreover, they must be technically efficient since this affects the production level and, consequently, the production costs. For that matter, Leite *et al*. (2013) and Leite *et al*. (2014) stress that such efficiency is impacted by several factors, such as the individual volume per tree and slope of the terrain, which interact with each other either isolated or dynamically. This justifies the need of knowing in detail the effects of these variables so as to plan operations aiming at reducing costs and settling production.

The determination and quantification of these influential variables are determining factors for forest planning and success of operations, which contribute greatly to the optimization and economic viability of harvesting activities. This is so mainly because of Brazil's position as the fourth among the countries with the highest production cost (OLIVEIRA JÚNIOR *et al*., 2009; SANTOS *et al*., 2016).

In mechanized timber harvesting operations, one of the most used equipment for the cutting step is the feller-buncher, developed in North America. This machine is a tractor with rotated tires or mats, and hydraulic arm and head, used to cut various trees in one operating cycle. This function is possible due to a system of accumulation of trees fitted in its own head (SPINELLI *et al*., 2007; OLIVEIRA JUNIOR *et al*., 2009; HIESL; BENJAMIN, 2013).

Therefore, due to adjustments made to the operationalization of the feller-buncher in South America and the several factors that affect the operational productivity and, consequently, timber harvesting costs, technical and economic values can vary considerably for each working condition. Thus, the uncertainty can be incorporated into technical-economic studies directed to timber harvesting, aiming at the management of forest resources, through the probability of occurrence of values, which allow to describe the behavior of the most relevant variables.

Since the uncertainties are common, the acknowledgement of the impact that these can cause generates opportunities to optimize the production systems, creating ways to make them more controllable (CHENG; ROY, 2010; PAJARES; LOPEZ-PAREDES, 2011). One of the ways to incorporate the uncertainties of a forestry project is through the Monte Carlo method. According to Loizou and French (2012), when considering this incorporation, the analysis of a project is no longer based on a deterministic result, but through an area that represents the uncertainty, with the possibility of understanding and quantifying their effects on project budgets (KWAK; INGALL, 2009).

The usage of the Monte Carlo method enables the incorporation of technical and economic elements, essential to analyze the sensitivity of the most relevant variables of a stochastic model. Additionally, it allows the obtainment of probability distributions and of the range of uncertainties, making it possible to measure the risk presented in the tails of the distribution set.

For that matter, and considering that the uncertainties are related to calculation methodologies, to all the data and to the environment of a forest stand, this study aims at building stochastic models to analyze the behavior of the probabilistic cost of the production in the felling operation with feller-buncher in two classes of slope terrain through the Monte Carlo method.

MATERIALS AND METHODS

Area of study

The study was conducted in the Central-West region of the state of São Paulo, Brazil, (23 ° 06' N, 48° 36' E), in the summer. According to the Köppen-Geiger climate classification, the climate of the area is temperate humid, with dry winter and hot summer, and annual average temperature of 19.7 °C. In general, the area has an average relative humidity around 74%, with average annual rainfall of 1,372.7 mm and a relatively dry season from July to September. Geographically, it has predominantly Yellow Red Latosol, Psamytic Distrophic (SANTOS *et al*., 2013). Furthermore, it has separate slope classes according to the Brazilian soil classification. Therefore, it has 0 to 3% of flat relief and 8 to 20% of undulating relief, with strongly acid soils (pH < 4.5).

In this area, there was a stand of six-year-old *Eucalyptus* sp., intended for the production of plates. The stand was planted in 3 x 2 m spacing and had an average diameter at breast height (DBH) of 15.94 ± 3.85 cm, average height of 24.58 ± 4.78 m and average volume of 0.23 ± 0.11 m^3 per tree, conducted under high shaft. The wood volume was estimated from the forest inventory, considering the stratified random sampling.

Data collection

The harvest system was of long logs, thus, a John Deere 903k feller-buncher was used, with 13,331 accumulated hours of use, 294 horsepower, wheeled conveyor, hoist for maximum range of 6.7 m and FS22B felling head, with 558.8 mm cutting capacity and accumulation capacity of 0.48 m^2. The work extension of the feller-buncher was composed of three tree rows, six meters wide. The bundles of trees were dumped on the ground at an angle of 90°in relation to the alignment of the planting, in order to facilitate the next step of extraction.

Working time data were registered through time and movements studies, through continuous-time timing. The operating cycle of the equipment was divided by working elements, which were performed in a regular sequence, contributing effectively to the timber harvesting operation. The cycle is represented by the time spent to fell the trees, dump the bundles of trees on the ground, return to cutting position and accumulate the bundles of trees.

The time data of each working cycle element were submitted to the Shapiro-Wilk test in order to verify the assumption of normality. For comparison of the mean times of each element, in each relief and between them, the analysis of variance was applied (ANOVA), complemented with Tukey test at 5% level of significance.

According to Mousavi (2012), a sample shall be timed in order to obtain a conclusion with a certain degree of statistical validity. In this perspective, 50 operating cycles were observed for a preliminary estimate of the sample size in both reliefs, in order to obtain a sufficiently representative sample. The sample was taken from the mean times of the work cycle elements ($\bar{x}$) and standard deviation of the sample (s) (STEVENSON, 2001), at 95% confidence level and 5% of error, as described in Equation 1.

(1) $$n = \left(\frac{z\,s}{a\,\bar{x}}\right)^2$$

In which:
n - sample size;
z - number of standard deviations in a normal distribution necessary to obtain the desired confidence level;
s - standard deviation of the sample;
a - percentage of precision desired;
$\bar{x}$ - sample mean.

Technical analysis

From the relationship between effective time of work and volume of trees cut, the productivity of the feller-buncher was determined (Equation 2), that is, the rate of production per unit of time of the felling operation, which is extremely relevant both for forest planning and for forest management.

(2) $$E_p = \frac{v}{h}$$

In which:
E_p - effective productivity of the feller-buncher ($m^3\ h^{-1}$);
v - volume of wood cut (m^3)
h - hours of work (h).

Cost analysis

The monetary values were expressed in commercial American dollar, official of the Central Bank of Brazil, sold per hour of work (US$ h^{-1}) (CENTRAL BANK of BRAZIL, 2017). Therefore, the price of the foreign currency was considered as exchange rate and was measured in units and fractions of the national currency, which was R$3.1932 (27/09/2017).

The operating cost of the feller-buncher was estimated in accordance to the methodology of cost control on timber harvesting recommended by the Food and Agriculture Organization of the United Nations (FAO, 1992). These costs were classified into: fixed costs of depreciation; interest on capital; workmanship; insurance; and rates on property. Variable costs comprised the monetary values with fuel, maintenance and repairs, spare parts, and lubricating oils and greases. The economic life of the feller-buncher was estimated at five years, with resale value of 20% of the purchase price. Moreover, the social security contributions corresponded to 134% of the salary of the feller-buncher operator.

Interest on equity, arising from the use of the money invested in the feller-buncher, were calculated by the rate of interest determined by the Capital Asset Pricing Model (CAPM) described in Equation 3. With this in mind, the interest rate of 2.07%, risk-free, was applied, issued by the Treasury Department of the United States of America for the period of five years (period of the economic life of the feller-buncher), of factor β_e 1,12 for forest product industries and the market risk premium of 4.52%.

(3) $$K_e = k_{rf} + \beta_e(k_m - k_{rf})$$

In which:
K_e - cost of equity;
k_{rf} - risk-free interest rate
β_e - systematic risk of the forest industry;
k_m - expected return of a market portfolio;
$(k_m - K_{rf})$ - market risk premium.

The production cost of the operation, determining both the definition of the harvesting mode and the profitability of products from forest-based companies, was calculated by the ratio between the hourly operating cost and the effective productivity of the feller-buncher (Equation 4).

$$P_{co} = \frac{H_{oc}}{E_p} \quad (4)$$

In which:
P_{co} - production cost of the operation with the feller-buncher (US$ m^{-3});
H_{oc} - hourly operating cost of the feller-buncher (US$ h^{-1}).

Risk analysis

The Monte Carlo method was applied to the model so that stochastic solutions could be incorporated, with 100,000 iterations performed through the @Risk Copyright © 2016 Palisade Corporation software (2016). The random number generator Mersenne Twister was employed, ensuring the same initial parameter for the model run. Thus, from the initial representation of the most important input variables, that is, effective productivity and hourly operating cost (inputs), a stochastic model was built to express the production cost of the operation (output) in terms of probability.

For the series of values of the effective productivity, the Kolmogorov-Smirnov (K-S) test was used, at 1% level of significance to check the normality of the data. As for the hourly operating cost and the production cost of the operation, probability distributions were set by the Bayes Information Criterium (BIC). In order to measure the degree of linear association between inputs and outputs, Spearman's rank correlation coefficient was used (ρ_S), at the significance level of 5%.

RESULTS

Working hours of the operating cycle

During the period of field study, the total effective working time was 6 hours and 45 minutes. In flat relief, it was estimated that at least 100 work cycles would be required. However, 268 cycles were observed. Regarding the undulating relief, the minimum number of work cycles required was 58. However, 238 cycles were observed. During this period, 1,915 trees were felled in the flat relief, which corresponded to 478.7 m^3, while in the undulating relief 1,735 trees were felled, which represented 381.7 m^3.

Among the global distribution of the total effective time of the monitored working cycles, the mean times for felling the trees were the most representative in both reliefs analyzed (Table 1). Moreover, the times differed statistically among the reliefs ($p < 0.05$), followed by the time spent to accumulate the bundles of trees, which were similar to each other by Tukey test at 5% of probability of error.

Table 1. Descriptive statistics of the times (minutes) of the feller-buncher work cycle elements.
Tabela 1. Estatística descritiva dos tempos (minutos) dos elementos do ciclo de trabalho do *feller buncher*.

Descriptive statistics	Flat relief				Undulating relief			
	Felling	Dumping	Returning	Accumulating	Felling	Dumping	Returning	Accumulating
Mean	0.46b	0.09b	0.12a	0.30a	0.52a	0.10a	0.10b	0.23a
SD	0.09	0.03	0.06	0.18	0.13	0.04	0.07	0.16
Min.	0.12	0.05	0.05	0.10	0.13	0.03	0.03	0.05
Max.	0.82	0.22	0.37	0.72	1.27	0.30	0.55	0.58
P5	0.33	0.05	0.07	0.13	0.36	0.05	0.03	0.08
P95	0.63	0.15	0.22	0.65	0.75	0.18	0.22	0.58

SD: standard deviation; min: minimum; max: maximum; P5: 5% percentile; P95: 95% percentile. Means followed by the same letter in the line do not differ statistically at 5% of significance by the Tukey test.

Effective productivity

The data adherence to the Normal distribution was confirmed by the Kolmogorov-Smirnov test, for the values of effective productivity observed in flat relief (K-S = 0.07) and undulating relief (K-S = 0.05). When considering the effective productivity in the flat relief, Normal distribution fitted the best (BIC = 2391.95), with a mean of 160.43 m^3 h^{-1} and standard deviation of 23.61 m^3 h^{-1}, and with a symmetric curve around the mean.

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Regarding the effective productivity observed in the undulating relief, Normal distribution fitted the best (BIC = 2218.77), with a mean of 132.88 $m^3 h^{-1}$ and standard deviation of 26.60 $m^3 h^{-1}$.

Hourly operating cost and timber harvesting cost

Based on the probabilistic value of the feller-buncher's hourly operating cost, and taking into account the selection criterion of BIC models, it was observed that the Normal distribution fitted the best, with a mean of US$81.74 h^{-1} and standard deviation of US$2.34 h^{-1}, which allowed the symmetric modeling of the data (Figure 1).

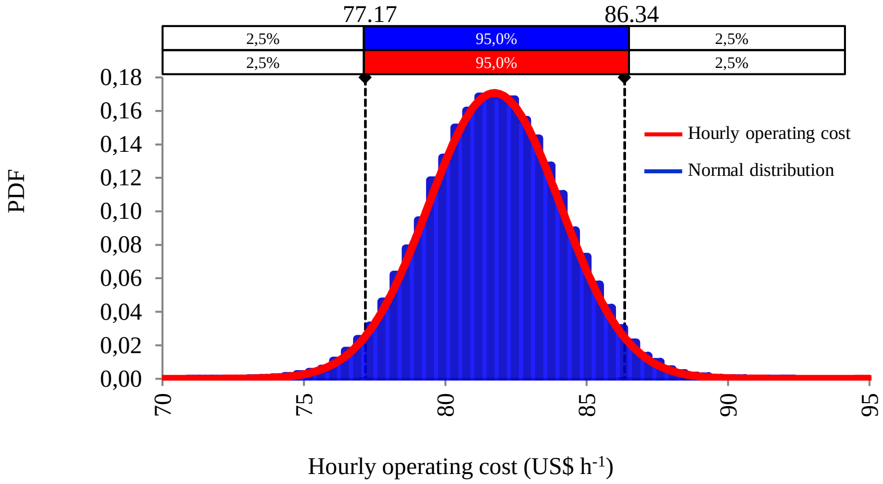

Figure 1. Probability Density Function (PDF) of the feller-buncher's hourly operating cost.
Figura 1. Função Densidade de Probabilidade (FDP) do custo operacional horário do *feller buncher*.

In the tornado diagram (Figure 2), the individual effect of each item of the feller buncher's hourly operating cost can be observed. At the upper end, the item with the greatest influence in the stochastic model is presented, while the lower end presents the item with the least influence. The maximum and minimum limits of each item are expressed by the distance between the line of the mean value (dashed line) and the value that can be obtained (ends of the vertical bar), which did not present symmetry for the analyzed condition.

Consequently, the fuel cost was the input with the highest statistically significant positive correlation (ρ_s = 0.91) (p-value < 0.01). Moreover, this input represented 50.4% of the hourly operating cost, followed by depreciation (ρ_s = 0.29), which accounted for 17.1% of the hourly operating cost. Regarding the expenses with spare parts, maintenance, and repairs, sensitivity analysis demonstrated a positive correlation with the variable of interest of 0.19 and 0.13, respectively, which corresponded to 19% of the hourly operating cost.

In the analysis, the return on capital, that is, the interest on equity, estimated through CAPM, resulted in a rate of 11.4%, demonstrating a low positive correlation (ρ_s = 0.09) with the hourly operating cost. The remaining cost items resulted in correlations considered to be weak ($\rho_s \leq 0.08$). However, such cost items may influence the final value under analysis: the production cost of the feller-buncher operation.

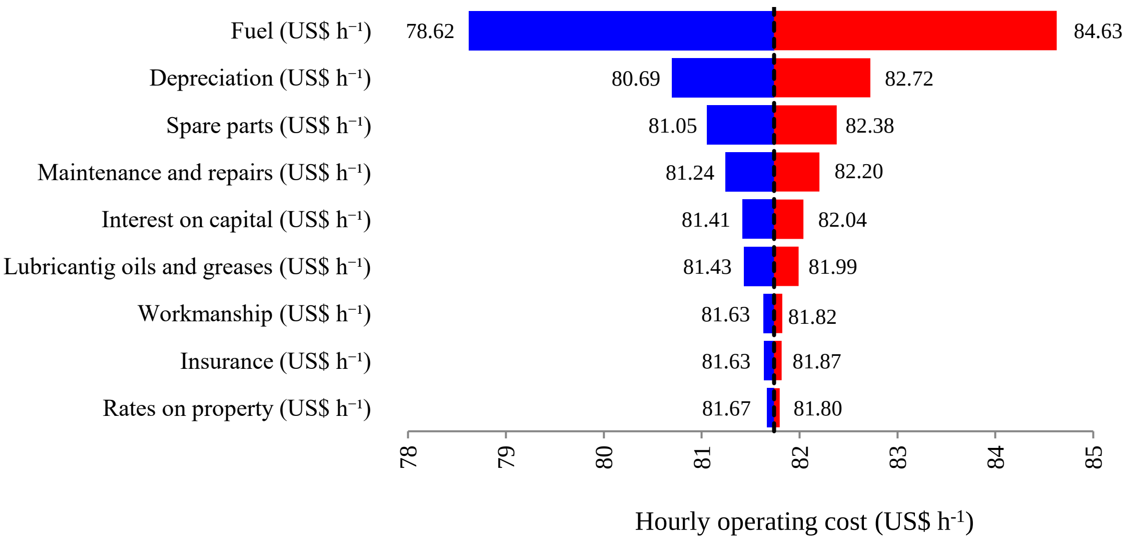

Figure 2. Individual effect of the cost items over the feller-buncher's mean hourly operating cost.
Figura 2. Efeito individual dos itens de custo sobre o custo operacional horário médio do *feller buncher*.

As for the production cost of the operation, both in flat relief and undulating relief, the mean and the standard deviation of the Lognormal distribution were adjusted (Figure 3). For the flat relief, the mean production cost of the operation was US$0.52 m^{-3} and the standard deviation was US$0.08 m^{-3}, with 95% of the generated values falling below US$0.67 m^{-3}. The mean production cost of the operation for the undulating relief was US$0.64 m^{-3} and the standard deviation was US$0.14 m^{-3}, with 95% of the probabilistic values lower than US$0.91 m^{-3}.

When considering the relationship between the production cost of the operation for the flat relief and the feller-buncher's effective productivity, a negative coefficient of Spearman's rank-order correlation was obtained (ρ_s = -0.98). For the hourly operating cost, this coefficient was positive (ρ_s = 0.18). For the undulating relief, these inputs presented similar values to the ones for flat relief, with coefficients of -0.99 and 0.14, respectively.

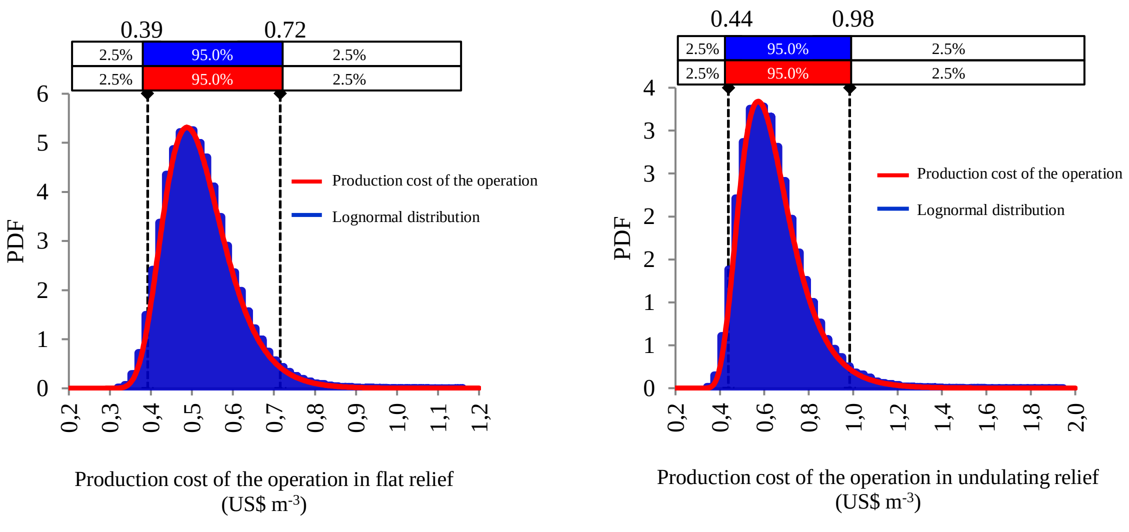

Figure 3. Probability Density Function (PDF) of the production costs of the operation with the feller-buncher in flat and undulating relief.
Figura 3. Função Densidade de Probabilidade (FDP) dos custos de produção da operação com *feller buncher* em relevo plano e relevo ondulado.

DISCUSSION

In the analysis of the sample size, the initial estimate proved to be necessary in order to obtain accurate results. However, due to the technical conditions offered for the development of the study, a larger sample size was chosen. Such choice ensured a greater confidence in the estimate of the times of the work cycle elements, due to the reduction of the desired maximum error, which resulted in 3.1% for the observations in flat relief and 2.4% for the measurements obtained in undulating relief.

Thus, the scientific study of times and movements provided detailed information about the elements of the work cycle, such as the time of the related activity, that is, the time spent to fell the trees, which demanded 67.1% of the effective time of work during the harvest in flat relief and 70.8% in undulating relief. These percentages are similar to the results of Nascimento *et al*. (2011), who found that 65% of the time was spent in felling the trees, with the tipping of the bundles forming a 90° angle with the planting row. The percentages are also similar to the findings of Simões *et al*. (2010), who found an average percentage of 68.2% for this element, with the feller-buncher in an extension composed of three tree rows. Therefore, the difference between the times of this element of the work cycle can be explained by the relief categories, since the harvest was conducted in a homogeneous forest with similar climatic conditions and, especially, monitored by the same feller-buncher operator.

The element returning to cutting position was the second most representative among the elements of the work cycle, for it consumed 17.4% of the time for the flat relief and 15.2% for the undulating relief. The most likely factor for this expense is the angle for the dumping of the bundles of trees, because the angle can increase or decrease the time of this element and, according to Lima and Leite (2014), angles of 45° or 90° can be formed in relation to the plating row. However, the angle for the dumping of these bundles is associated with simplifying the subsequent operation, which may be the bucking of wood within the tree stand or the skidding of the trees to the roadside. The dumping element consumed an average of 12.6% of the time, followed by the time spent to accumulate the bundles of trees, which demanded 2.3% of the effective time of work.

Therefore, the study of times and movements, which can be considered as the basis of the rationalization of the productive factors, enabled to determine the effective productivity, modeled by a probability distribution that determined the average effective productivity and the dispersion of the data. Thus, the stochastic values were higher than those found by Simões *et al*. (2014) e Miyajima *et al*. (2016), whose studies were conducted in similar conditions of equipment, relief and forest stand. It is worth noting that the effective productivity of the machines used in timber harvesting is influenced by several factors, such as the slope of the terrain, the soil type, the experience of the operator, the tree volume, among others that can be previously identified, but with different degrees of precision. However, these factors can be evaluated by methods that allow the evaluation and measurement of operational risks.

Regarding the hourly operating cost of the machines used in timber harvesting, there are different methodologies for this calculation. However, Ackerman *et al*. (2014) stress that the results given by each of them are slightly different. This characteristic can be explained due to the several factors that compose this hourly operating cost, which should be evaluated as sources of uncertainty. If not treated as such, the analyses will be subject to varied errors, such as the analysis of timber harvesting cost, for example.

Thus, by assigning a probability distribution for each source of uncertainty, that is, for each item composing the hourly operating cost, a range of occurrence of the value under analysis was obtained and, therefore, a probability distribution was adjusted for the hourly operating cost of the feller-buncher. As a result, the probabilistic value of the hourly operating cost was between US\$77.17 h^{-1} and US\$86.34 h^{-1}, with a probability of 95%. The hourly operating cost values found by Seixas and Batista (2014) for three feller-buncher models are within this range. These authors used the same methodology of the present study, but in a deterministic way.

From the average value, the fuel cost, for being the input with the greatest effect over the hourly operating cost, underwent a positive change of up to 3.8% and a negative change of up to 3.5%. By keeping the remaining inputs unchanged, the hourly operating cost could increase by US\$2.89, but it would provide a reduction of US\$3.12 per hour of work. Analogously, the depreciation is another input that should be monitored due to the positive effect of up to 1.3% and the negative effect of 1.2%. Therefore, the hourly operating cost would be reduced by US\$1.05 or would increase US\$0.98 per hour of work. The remaining inputs resulted in both positive and negative variations lower than 1%.

When analyzing a forest investment, managers establish a series of guidelines, such as the harvesting mode. However, the choice of the mode is associated with harvesting costs, which can derail both the capital investment and the price of the final product. Thus, the analysis of harvesting costs conducted from stochastic variables allowed the establishment of probabilities of occurrence and the association between the variables of interest. Therefore, the probabilistic value of the production cost of the operation in flat relief varied 15.4%, while in undulating relief the variation was 21.9%, compared to their respective mean values.

The Monte Carlo technique provided results based on probabilities and associations, such as the degree of relationship between the effective productivity and the production cost of the operation. These results showed negative association coefficients and are considered strong for having a monotonic relationship, that is, these variables tend to have a contiguous increasing or decreasing behavior.

CONCLUSIONS

- The application of the Monte Carlo method allowed obtaining probabilistic distributions that describe the behavior of the variables of interest. Also, it allowed a plausible analysis of the production process and related costs, since it is based on the calculation of probabilities of occurrence of the events of these variables.
- Based on the mean probabilistic value, it was verified that the behavior of the production cost of the operation in flat relief was lower than the production cost of the operation in undulating relief.
- The fuel cost was the most relevant variable in terms of economic risk, for it presented a strong positive correlation coefficient with hourly operating cost.

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