EFFICIENCY OF COFFEE MECHANICAL AND SELECTIVE HARVESTING IN DIFFERENT VIBRATION DURING HARVEST TIME

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ABSTRACT: The aim of the present work was to assess the operating performance of mechanical harvesting of the fruit of coffee trees (*Coffea arabica* L.) with a KTR® Advance harvester using a "neuro-fuzzy" system which considered the variation of the vibration of the rods and the maturation index of the fruit. The evaluations were carried out fortnightly for 70 days in treatments with vibration levels of 13.33, 15.00 and 16.66 Hz. The volume collected was recorded in each period according to the maturation of the crop as well as determining the percentage of fruit in their maturation according to the used vibration. Based on the "neuro-fuzzy" system, it was possible infer with 92% the harvest efficiency using the KTR® harvester, noting an increase in harvest efficiency by increasing the vibration of the harvester shakers and the coffee fruit maturation index. It was also concluded that with increased vibration, there was an increased percentage of green and selective fruit harvested. Mechanical harvesting was easier when the rate of crop maturation increased. Analyzing the average volume harvested during the entire period, we observed no significant difference in the vibrations of 13.33 and 15.00 Hz, but there were increases of 30.90% and 37.45% when used at higher vibration.

Index Terms: Coffee crop, operational performance, maturation.

EFICIÊNCIA DA COLHEITA MECÂNICA E SELETIVA DO CAFÉ EM DIFERENTES VIBRAÇÕES, AO LONGO DO PERÍODO DE COLHEITA

RESUMO: *Objetivou-se, com o presente trabalho, avaliar o desempenho operacional da colheita mecânica dos frutos de cafeeiros (Coffea arabica L.) com uma colhedora KTR® Advance por meio de um sistema 'neuro-fuzzy' considerando-se a variação da vibração das varetas e do índice de maturação dos frutos. As avaliações foram realizadas quinzenalmente, durante 70 dias, em tratamentos com níveis de vibração de 13,33; 15,00 e 16,66 Hz. Foi contabilizado o volume colhido em cada período de acordo com a maturação da cultura, bem como a determinação da porcentagem de frutos colhidos em seus respectivos estádios de maturação em cada vibração utilizada. Com base no sistema 'neuro-fuzzy', foi possível inferir com 92% da eficiência de colheita da colhedora KTR®, constatando-se aumento de eficiência de colheita com o aumento da vibração das varetas da colhedora e do índice de maturação dos frutos de café. Concluiu-se também que, com o aumento da vibração, há um aumento na porcentagem de frutos verdes colhidos e que a colheita mecânica seletiva é facilitada com o aumento do índice de maturação da cultura. Analisando o volume médio colhido durante todo o período, foi possível verificar que não houve diferença significativa nas vibrações de 13,33 e 15,00 Hz, mas houve incrementos de 30,90% e 37,45%, quando utilizada a maior vibração.*

Termos para Indexação: *Cafeicultura, desempenho operacional, maturação.*

1 INTRODUCTION

In the Brazilian agribusiness the coffee crop stands out as a product that generates great volumes of earnings to the country and also could be considered, according to Trabaquini et al. (2010), the economical base to many municipalities and regions. Since this crops is so important to Brazil and due to its high production cost (OLIVEIRA et al., 2007a; RIBEIRO et al., 2009), the mechanization of the production process could be considered as a practice that reduces these costs.

In recent decades, due to the significant increase in area available being occupied with coffee plantations, and the increasing reduction of manpower for harvesting, also coupled with economic factors, coffee producers began to opt for mechanical harvesting (ROSA et al., 2010). This technological breakthrough was only possible due to the development of the first harvester in Brazil, in 1974, with the "Jacto" project, whose goal was to better understand the detachment of coffee (SILVA et al., 2008). Since then, there is a growing

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of research related to mechanical harvesting by the principle of vibration. Moreover, in recent years, from the work by Silva et al. (2007) and Silva, Teodoro e Melo (2008) evaluating the behavior of the force of detachment during the crop cycle, this parameter has to be correlated with the operational performance of mechanical and selective harvesting, with the purpose of harvesting the plant mechanically, specially the mature fruit, since this is the stage that makes the best drink out of the fruit.

According to Silva et al. (2008), this technological development has been favorable, especially for mechanized harvesting, contributing to more stable coffee production able to provide sustainable productivity in order to make it competitive, and provide improvements to the life of those people involved in the production process.

Mechanical harvesting of coffee is based on the principle of vibration in shaker fingers that intermingle with the coffee tree canopy and cause the detachment of the fruit. Green fruit comes off with higher levels of vibration or by direct impact with the fingers, while mature, withered, and dry fruit come off with lower vibrations (SILVA et al., 2007). Because of this, three adjustments can be done in the harvester in order to have a more effective harvest. They are: vibration, operating speed, and the distribution of shaker fingers. However, it is necessary to study the interaction between these factors, to enable better adjustment of the harvester seeking to increase the efficiency of harvesting according to the maturation of the fruit in the crop. According to Santos et al. (2010) the major frequencies and amplitudes provides the highest values of mature fruits ripening and the ripening efficiency by vibration was higher in the Mundo Novo cultivar than in the Catuaí Vermelho cultivar.

According to Läderach et al. (2011) and Silva et al. (2010), different fruit maturity show detachment strength statistically different and it's different for every cultivar. But, according to Ferraz et al. (2012) the coffee harvest is more difficult to study than crops such as cereals because of features such as plant shape, non-uniform maturation of the fruit and high humidity of fruits. Coffee is a perennial bush and each plant can have a different shape with differences in plant height, length and width, even with plants that are close together within a field. This feature makes harvesting and the design of coffee harvesters difficult because they involve removing the fruit by vibration. According to Oliveira et al. (2007a), the efficiency of harvest is directly influenced by the vibration of the shakers of the harvester KTR® and of reverse speed variation.

Alves et al. (2009, 2011) concluded that it was possible to validate and implement a system of fuzzy logic to estimate the process monocyclic Asian soybean rust. According to the author, it was observed that there was a greater correlation of estimates of the fuzzy logic system with the observed data than with the methods of nonlinear regression. When it is related to the soil fertility, Malta et al. (2008) concluded the small values of pH and the disequilibrium of the relationship among K, Ca and Mg could affect the coffee plant growing, development and yield when it was submitted to the organic management in the south of Minas Gerais state.

The aim of the present work was to assess the operating performance of mechanical harvesting of the fruit of coffee trees with a KTR® Advance harvester using a "neuro-fuzzy" system which considered the variation of the vibration of the finger shakers and the maturation index of the fruit.

2 MATERIAL AND METHODS

The tests were conducted in Capetinga Farm, Municipality of Boa Esperança, the state of Minas Gerais, whose geographical coordinates are 21°13'S and 45°34 W of Greenwich, with an average altitude of 930 m. The climate, according to Köppen, is classified as subtropical with a dry winter. The cultivar evaluated in the experiment was the Mundo Novo IAC 376/4, planted on land with slope average of 10%, spaced 4.0 x 1.0 m, with an average population of 2,500 plants per hectare.

The tests were conducted using completely randomized design (CRD) with five repetitions in random plots containing at least 40 plants on line in each plot. The parcels were properly characterized by determining the average pending charge of berry fruits (L plant-1) and the percentage of green, withered and dry coffee in the plant. The methodology used to determine the detachment average force was proposed by Silva et al. (2010).

All the tests were conducted using the Jacto KTR® Advance harvester pulled by a 55,16 kW front wheel drive coffee tractor. A rider works the harvester on one row of plants. Two harvester cylinders, equipped with shaker fingers which work horizontally and laterally, surround the coffee, harvesting the fruit through vibration effect which fall into the collection system and, after being cleaned, are transferred to a truck, or are bagged.

The speed of 1,600 m h-1 was established for the experimental trials as reference Oliveira et al. (2007b). This speed was kept constant for all treatments that had a variation of shaker fingers vibration, being used 800, 900 and 1000 cycles minute-1 (13.34, 15.00 e 16.50 Hz).

The experimental data was organized in tables and charts, using Microsoft Office Excel® and analyzed using Matlab R2006b®.

During mechanical harvesting with the KTR® Advance harvester the volume collected in L h-1 was determined from the percentage of fruit in different maturation stages (green, mature, withered and dry) for the different shaker fingers vibrations: 13.34, 15.00 and 16.50 Hz

The percentage of fruit in different maturation stages was made, after counting fruit from five samples of 0.50 L for each shaker fingers vibration. The total volume of the fruits harvested was determined using a graduated measure of 20.00 L and by measuring the time required for it to reach maximum volume.

The maturation index (MI) was determined based on the percentage of green fruit (equation 1). Therefore, it was necessary to count the fruit obtained from five samples of 0.50 L of total volume of pending charge found in plants of each plot. The final maturation index was obtained by averaging the five values of MI found in each repetition, where the maturation index is the sum of the mature fruit, withered and dry (equation 1)

$$\text{Harvest Ef.} = \frac{\text{Pending load}}{\text{harvested vol.} + \text{groud vol.}} \times 100$$

To obtain the total maturation degree (MD), the weighted average of the fruits in each stage of maturation was made, represented by its weight and the percentage of fruit in their maturation stages, as follows according to Silva et al. (2010) (equation 2):

$$MD = \frac{4 \cdot (\%dry) + 3.8 \cdot (\%withered) + 2 \cdot (\%mature) + 1 \cdot (\%green)}{(\%dry + \%withered + \%mature + \%green)}$$

where:
MD - is the maturation degree of the parcel;
% - Is the percentage of fruit in each stage of maturation, expressed in decimal.

The efficiency of the harvest in three periods was evaluated, characterizing the beginning, middle and the end of harvest period. These periods were characterized based on the percentage of mature fruits as described by Souza, Queiroz e Rafull (2006); the ability to detachment of the fruits is directly proportional to the percentage of ripe fruit on plant. The tests were done with mechanized harvesting using vibration levels of 13.33, 15.00 and 16.66 Hz, and the resulting volume harvested was compared to determine harvest efficiency with respect to the amount of fruit on the plant.

For the use of the “neuro-fuzzy” system relevancy functions and rules of inference were set up by neural networks. The system used the Sugeno (1985) implication operator because it is easier to adapt the technique of using neural networks in the construction of “Fuzzy” logic systems, and is the best application of this method in modeling nonlinear systems (TSOUKALAS; UHRIG, 1997).

The fuzzy logic system was subdivided in five parts: fuzzification of the input variables, application of the fuzzy operator (and, or) in the antecedent, implication from the antecedent to the consequent, aggregation of the consequents across the rules, and defuzzification. The fuzzy system was configured as follows: ‘And’ method using algebraic product (prod), or method using a probabilistic method (probor) also known as the algebraic sum like: probor (a,b) = a + b - a * b, implication method (imp method) using minimum operator (min), aggregation method using maximum operator (max) and defuzzification method using weighted average method (wtaver). The ‘and’ operator was used as an inference basic step T-norm, related to a two-input function that describes a superset of fuzzy intersection (and) operators, including minimum (min) and algebraic product (prod). The ‘or’ operator was used as an inference basic step T-conorm in fuzzy implication process, also known as S-norm. It consisted in a two-input function describing a superset of fuzzy union (or) operators using algebraic sum. The implication method used the degree of support for the entire rule to shape the output fuzzy set. The aggregation combined the consequents of each rule in a single fuzzy set. Defuzzification was used to transform a fuzzy output of a fuzzy inference system into a crisp output. Sugeno (1985) fuzzy inference was adopted as a systematic approach to generate fuzzy rules from a given input-output data set due to its less time-consuming and mathematically tractable defuzzification operation.

The observed and predicted values by the ‘neuro-fuzzy’ system were compared using linear regression in order to observe the performance of the model to describe the operational performance of the harvest (Figure 1).

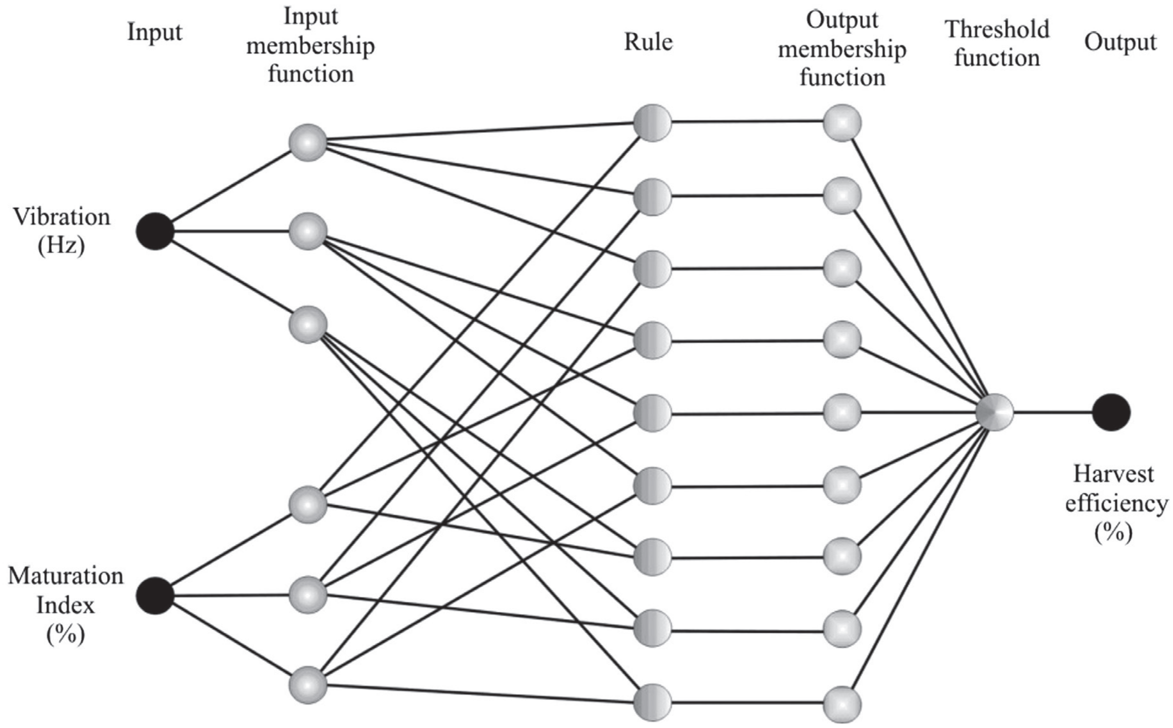

FIGURE 1 - Architecture of neural network system used to define the "neuro-fuzzy" system to estimate the efficiency of the harvest of the KTR® harvester.

3 RESULTS AND DISCUSSION

The satisfactory implementation of the 'neuro-fuzzy' system to describe the operational performance of the harvester KTR® was obtained. An increase in the harvest efficiency was found by increasing the vibration of the harvester shakers and of the cultivation maturation index (Figure 2), in order to describe 91.00% of the harvest efficiency by comparing the observed values to those estimated by the developed model (Figure 3).

Oliveira et al. (2007b) also found greater efficiency of harvest under increased vibration. According to the author, there was an increase of 29.25% in the harvest efficiency, and 31.12% in defoliation, comparing the lowest to the highest vibration.

As seen in Figure 2 and 3, the efficiency of mechanical harvesting is directly proportional to the fruit maturation index and the level of mechanical vibration applied to the coffee fruits. Bigger vibrations favor a higher loosening of the fruit, however, it contributes to a greater amount of green fruit present in the total mass collected.

As described previously the maturation index is the sum of mature, wither and dry fruit, it is important to note that the maturation index and degree of maturation are correlated, since the degree of maturation depends on the percentages of fruit in those maturation stages and on the weight in each maturation degree (Figure 4). However, the larger the maturation degree is, the more mature fruits are in the plant, since the biggest possible maturation degree is 4.0, and the smaller the maturation degree is, more green fruit will be present in the plant, considering that the minimum degree of maturation is 1.0.

We can see in the Figure 5, where the linear model of the detachment average force is represented for detachment of coffee fruit at different stages of maturation, the greater the degree of maturation is, the lowest average force of detachment of the fruits (Table 1). It is concluded that the force of detachment and efficiency of mechanical harvesting are correlated. That is, the smaller the force for detachment of the fruit, the greater the efficiency of mechanical harvesting will be.

The data in Tables 2, 3 and 4 shows, for three different harvest times, the results of volume and percentage of fruit harvested at different stages of maturation to the three levels of vibration used. It was observed that with increased vibration, the volume collected increased however, it also resulted in a greater removal of green fruit from the plant.

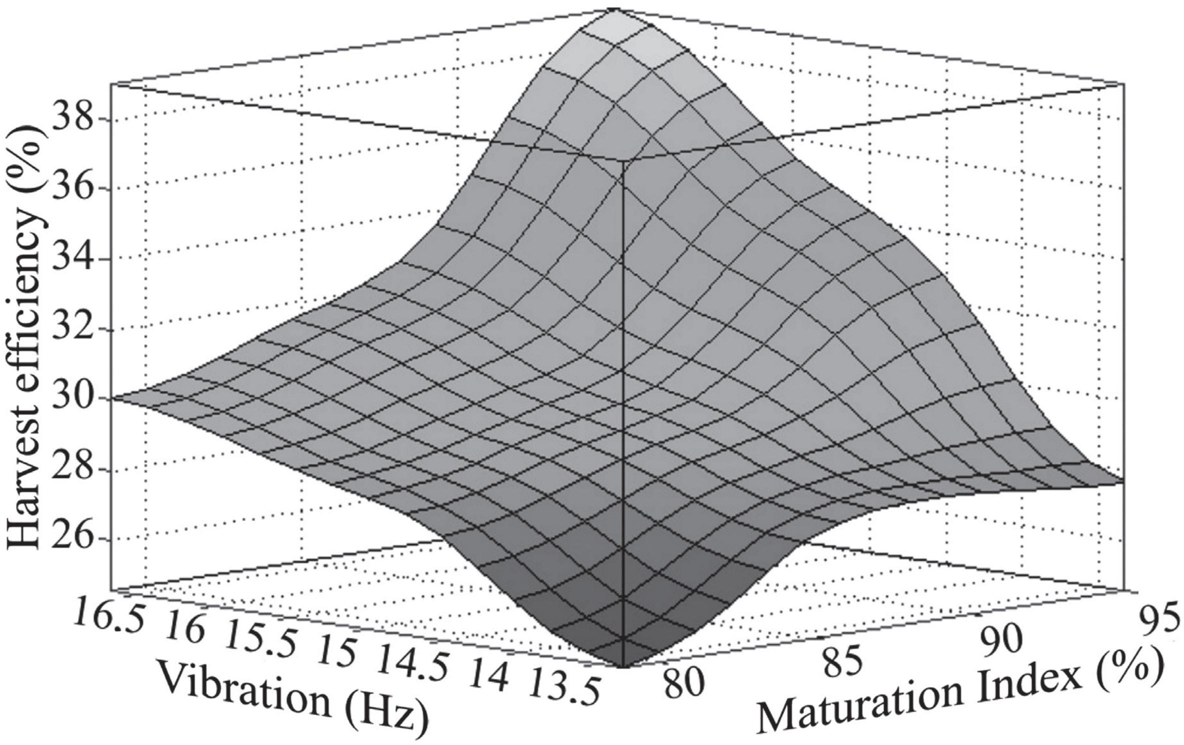

FIGURE 2 - Control Surface of the "neuro-fuzzy" System (NFS) used to describe the efficiency of harvest with the KTR harvester.

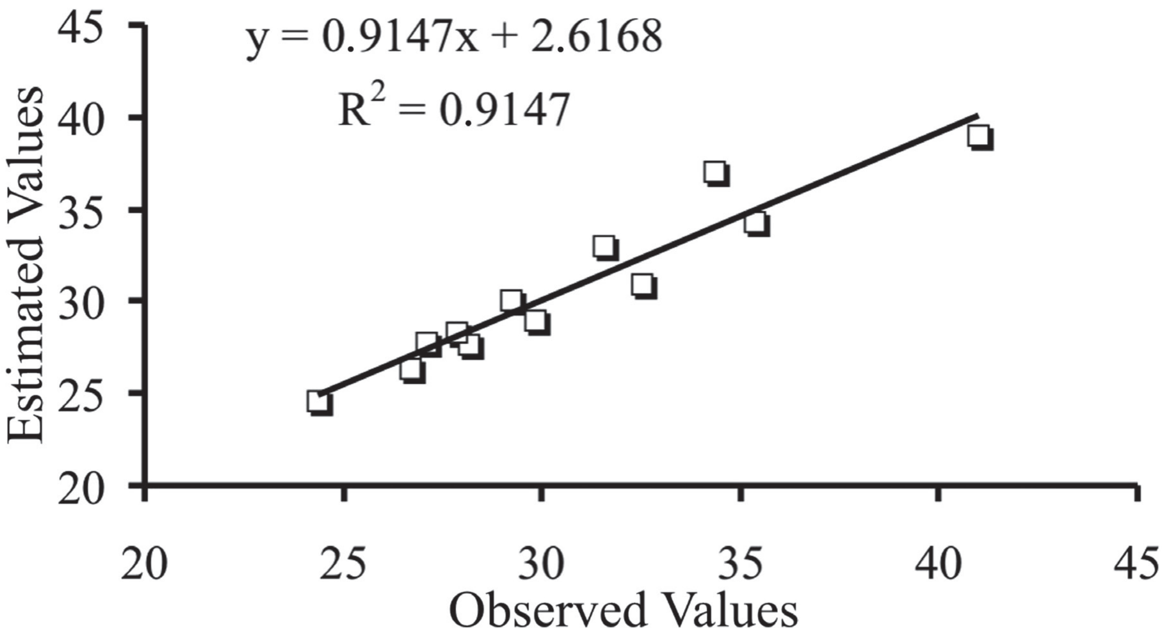

FIGURE 3 - Linear relationship between values observed and estimated by the "neuro-fuzzy" model used to describe the efficiency of harvesting with KTR harvester.

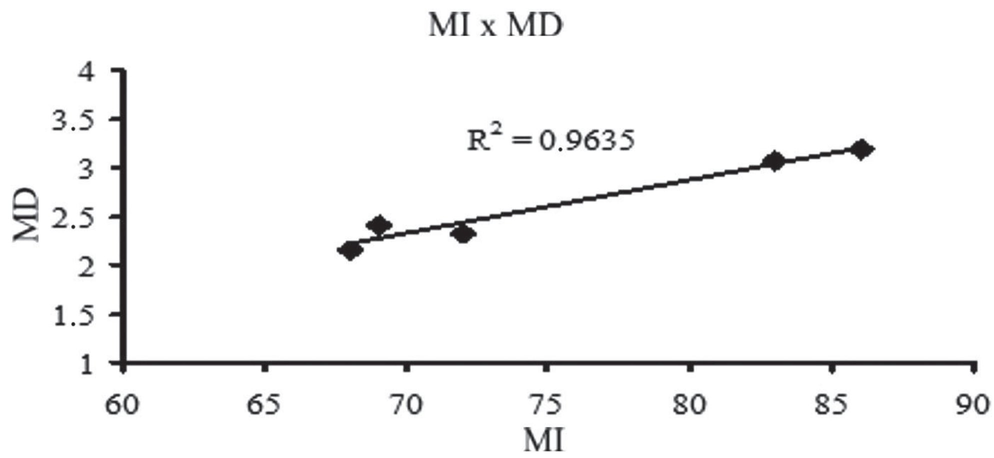

FIGURE 4 - Linear relationship between the maturation index (MI) and the maturation degree (MD).

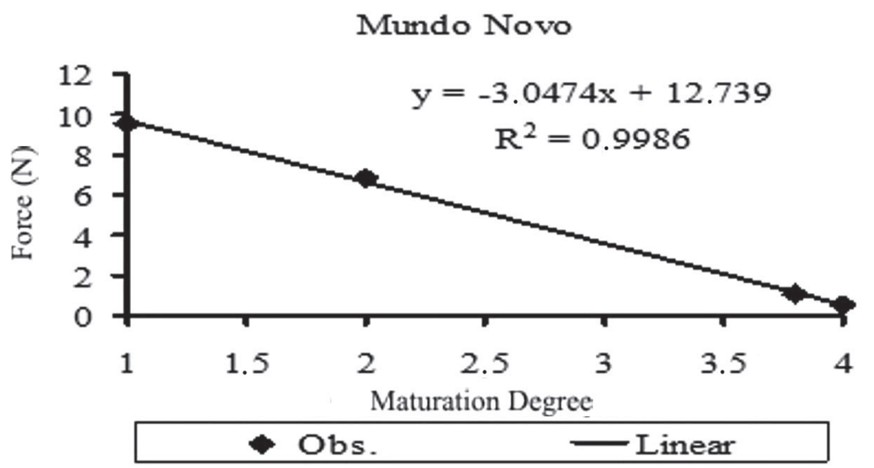

FIGURE 5 - Linear model for Mundo Novo cultivar, throughout the evaluation period.

TABLE 1 - Detachment average force (N) of the fruits in the maturation green and mature throughout the evaluation period.

Maturation*	Evaluation period		
	May 30	June 13	June 22
Green	7.61 D	11.22 C	10.34 C
Mature	6.08 C	7.21 B	7.00 B
Difference	1.53	4.01	3.34
Wither	0.89 B	1.25 A	1.26 A
Dry	0.42 A	0.83 A	0.79 A

Averages followed by same uppercase letters in the columms do not differ according to the Scott-Knott test.

* Significant by test f ($p<0.05$).

TABLE 2 - Volume and percentage of the fruits harvested in different stages of maturation, for levels of the finger shaker vibration used in the first assessment in May 30.

Mundo Novo Cultivar	MI = 69.06% and MD =2.70		
Hz vibration (cycles.min^{-1})*	13.33 (800)	15.00 (900)	16.66 (1000)
Volume harvested (Measures.h^{-1})	29.25 a	36.64 a	45.22 a
Harvest efficiency (%)	18.60	23.29	28.75
Fruits harvested in different stages of maturation (%)			
Green	2.55 A a	5.16 A a	6.77 A a
Mature	38.27 C a	41.52 C a	42.62 C a
Wither	35.64 C a	29.69 B a	26.51 B a
Dry	23.53 B a	23.63 B a	24.10 B a
cv = 18.07%			

Averages followed by same uppercase letters in the columms and lowercase in the lines do not differ according to the Scott-Knott test.

* Significant by test f ($p<0.05$).

TABLE 3 - Volume and percentage of the fruits harvested in their different stages of maturation, for levels of the finger shaker vibration used in the second assessment in June 13.

Mundo Novo Cultivar	MI = 83.76% and DM =2.78		
Hz vibration (cycles min^{-1})*	13.33 (800)	15.00 (900)	16.66 (1000)
Volume harvested (Measures.h^{-1})	92.41 a	93.40 a	124.48 b
Harvest efficiency (%)	31.63	31.97	42.61
Fruits harvested in their different stages of maturation (%)			
Green	12.21 A a	16.25 B a	19.98 A a
Mature	15.87 A a	8.75 A a	11.98 A a
Wither	14.20 A a	19.57 B a	15.85 A a
Dry	57.70 B a	55.42 C a	52.18 B a
cv = 15.41%			

Averages followed by same uppercase letters in the columms and lowercase in the lines do not differ according to the Scott-Knott test.
* Significant by test f ($p<0.05$).

By the results in Table 2, regarding the harvest made on May 30, one can observe that the volume of fruit has a tendency to increase with higher levels of vibration of the harvester finger shaker, however, it did not differ significantly. Note that the larger volume collected 45.22 measurements.h-1 (1.0 measurement equal to 60 liters) occurred with vibration of 16.66 Hz and the lowest volume 29.25 measurements.h-1 occurred at 13.33 Hz, which is an expected behavior and was confirmed by Oliveira et al. (2007a) and Silva et al. (1997). In this case, the percentage of mature fruit harvested was high for the three vibrations employed, with lower percentages of green, up to 6.77%, which reflects the principle of selective harvesting, reaping a greater volume of mature fruit, even though a high percentage of green fruit in the plant on that date was 31%. Observed that in the beginning of the harvest, the harvested volumes were low, nearly 37 measurements h-1, with maximum efficiency harvest of 28.75%, within the vibrations used. However, the average percentage of mature fruit harvested is high, 40.80%, even with the vibration of 16.66 Hz, the percentage of green fruit harvested was low, 6.77%. It is important to remember that on that date, the force of detachment of mature fruit was 6.08 N (Table 1) and green fruit was 7.61 N, with the difference between the force of detachment of green and mature fruit of 1.53 N, which characterizes perfect harvest conditions.

TABLE 4 - Volume and percentage of the fruits harvested in their different stages of maturation, for levels of the finger shaker vibration used in the third assessment in June 22.

Mundo Novo Cultivar	MI = 86.11% and DM =2.98		
Hz vibration (cycles.min^{-1}) *	13.33 (800)	15.00 (900)	16.66 (1000)
Volume harvested (Measures.h^{-1})	98.89 a	101.57 a	133.47 b
Harvest efficiency (%)	28.75	42.61	45.69
Fruits harvested in their different stages of maturation (%)			
Green	4.65 A a	3.78 A a	7.08 A a
Mature	14.17 B a	16.76 B a	17.77 B a
Wither	21.49 C a	15.07 B a	15.25 B a
Dry	59.69 D a	64.39 C a	59.91 C a
cv = 12.64%			

Averages followed by same uppercase letters in the columms and lowercase in the lines do not differ according to the Scott-Knott test.

* Significant by test f ($p<0.05$).

However, the maturation index of 69.06% was still low.

In the second harvest period, which occurred on June 13 (Table 3) it shows that the biggest volume harvested was also the one with higher vibration 16.66 Hz, being 124.48 measures h^{-1}, which differed significantly. For this period the force of detachment of mature fruit was 7.21 N and green fruit was 11.22 N, with the difference between the force of detachment of green and mature fruit of 4.01 N. However, the percentage of green fruit harvested increased to 19.98%, which did not differ significantly from the lower vibrations. This percentage of green fruit can be considered acceptable, as Chalfoun and Carvalho (1998), established the green fruit limit at 20% of the total volume harvested. As the maturation index is higher than 80%, the highest vibration can be recommended, aiming at greater efficiency of harvest.

In the third harvest period on 22 June (Table 4), the largest amount collected was also with the vibration of 16.66 Hz, differing significantly from the others with only 7.08% green fruit and a high maturation index of 86.11%, which justifies the use of higher vibration, having a better efficiency harvest also.

In the third period of the harvest, the volume collected increased considerably, being an average of 111.28 measurements h^{-1} with the vibrations used. It is observed that on that date, the force of detachment of the mature fruit was 7.00 N, this values is greater than that observed in the first period and the strength of detachment green 10.34 N, was also quite high. Thus, the larger volume collected is correlated with a higher percentage of harvested fruit (R^2 = 0,9986), which differs significantly from the others, which is confirmed by the maturation rate of 86.11%, proving to be no longer possible to do a selective harvest in this period due to early harvest of the crop.

4 CONCLUSION

According to the methodology used and the results found was possible describe the operational performance of the efficiency of harvesting of coffee fruit by the KTR® Advance harvester under interaction of the finger shaker vibration and the maturation index of culture through a "neuro-fuzzy" system.

The volume and efficiency of the harvest are directly related to the intensity of the vibration and the maturation index of fruit.

Mechanical and selective harvest can be managed in accordance with the force of detachment of the coffee fruit, along with the maturation index.

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