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MONITORING OF MECHANICAL SUGARCANE HARVESTING THROUGH CONTROL CHARTS

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ABSTRACT: Statistical process control in mechanized farming is a new way to assess operation quality. In this sense, we aimed to compare three statistical process control tools applied to losses in sugarcane mechanical harvesting to determine the best control chart template for this quality indicator. Losses were daily monitored in farms located within Triângulo Mineiro region, in Minas Gerais state, Brazil. They were carried over a period of 70 days in the 2014 harvest. At the end of the evaluation period, 194 samples were collected in total for each type of loss. The control charts used were individual values chart, moving average and exponentially weighted moving average. The quality indicators assessed during sugarcane harvest were the following loss types: full grinding wheel, stumps, fixed piece, whole cane, chips, loose piece and total losses. The control chart of individual values is the best option for monitoring losses in sugarcane mechanical harvesting, as it is of easier result interpretation, in comparison to the others.

KEYWORDS: quality, agricultural mechanization, moving average, EWMA.

MONITORAMENTO DAS PERDAS NA COLHEITA MECANIZADA DE CANA-DE-AÇÚCAR POR CARTAS DE CONTROLE

RESUMO: O controle estatístico de processo aplicado em operações agrícolas mecanizadas representa uma nova maneira de avaliar a qualidade com que as operações são realizadas. Neste sentido, objetivou-se neste trabalho comparar três tipos de ferramentas do controle estatístico de processo aplicadas às perdas na colheita mecanizada de cana-de-açúcar, para determinar qual o melhor modelo de carta de controle a ser utilizado para este indicador de qualidade. O monitoramento das perdas na colheita mecanizada foi realizado diariamente nas áreas agrícolas, de uma unidade produtora na região do Triângulo Mineiro - MG, durante o período de 70 dias, na safra de 2014. Ao final do período de avaliação, foram coletados 194 pontos amostrais no total, para cada tipo de perda analisado. As cartas de controle utilizadas foram: carta de valores individuais, média móvel e média móvel exponencialmente ponderada. Os indicadores de qualidade avaliados durante a colheita de cana-de-açúcar foram as perdas do tipo: rebolo inteiro, tocos, pedaço fixo, cana inteira, lascas, pedaços soltos e totais. A carta de controle de valores individuais é a melhor opção para o monitoramento das perdas na colheita mecanizada de cana-de-açúcar, por apresentar maior facilidade na interpretação dos resultados, em relação às demais.

PALAVRAS-CHAVE: qualidade, mecanização agrícola, média móvel, MMEP.

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INTRODUCTION

The use of statistical process control in agriculture has been disseminated, mainly, through the use of control charts of individual values or Shewhart charts, that can be considered a monitoring alternative for certain processes, for analysis of results and subsequent decision-making about determined activities associated with mechanized farming operations, aiming the increment of process quality level (ZERBATO et al., 2014). However, these studies used the same variation range between average and the control limits with value 3, using control charts of individual values and/or de moving amplitude.

On the other hand, when it comes to quality indicators from mechanized farming operations with high variance coefficients, as in sugarcane harvesting losses, due to the fact that the collection places are not the same and because harvest is carried out by labor, these can suffer variations that the individual values chart might or not be able to detect (ZHIQIANG et al., 2012), depending on its level of rigorousness.

In this context, control charts of exponentially weighted moving average (EWMA) seek to detect minimum variations throughout the process, also being able to indicate instability or stability of the evaluated process. It is highlighted that, by virtue of this control chart model be produced regarding exponentially weighted moving averages, the data set not necessarily presents normal distribution, situation that is usually contrary when considering control charts of individual values and moving average (MONTGOMERY, 2009). The control chart of moving average grants greater analysis rigorousness compared to the individual values chart (does not detect minor variations), but does not capture as detailed variations as the control chart of exponentially weighted moving average does, once the last is the most rigorous of all (AMIRI & ALLAHYARI, 2011).

However, most of times the sugarcane farming operations monitoring, the analysis, and the knowledge about the process for subsequent decision-making are not administered once it is difficult to know which chart model best fit to such quality indicator, independently from normality assumption and operation level of variability (VOLTARELLI et al., 2013). Nevertheless, agriculture-related studies, especially about sugarcane harvesting losses, are scarce, when regarding control charts of individual values, of moving average and of exponentially weighted moving average, that can also be used for monitoring and improvement of mechanized farming processes.

In this context, given that there are variations among the applied control chart models, due to data normality and high variance coefficient values of harvesting losses. The aim of this study was to compare three tool types of statistical process control employed in sugarcane mechanical harvesting losses, in order to determine which is the best control chart model to be used for this quality indicator.

MATERIAL AND METHODS

The experiment was conducted in agricultural area of a sugarcane plant, in the Triângulo Mineiro region– MG, Brazil, with approximate geodesic coordinates: Latitude 20º01’29” S and Longitude 48º56’25” W, with average altitude of 516 meters. The average declivity of the surrounding areas is around 3 to 9%, and the predominant climate is Aw in accordance with KOEPPEN classification (1948). The collected soils present textures varying from sandy to clayey, with predominance of clayey soils.

The cane field position, using a standard right-angle triangle, was considered lying-down (23%), lodged (35%) and upright (42%), over the harvesting period, with such variation derived from different harvested sugarcane varieties, as well as influence of external factors (winds) that contributed to predominance of lodged and lying-down positions. The average productivity of harvested areas throughout monitoring was of 80.94 Mg ha^{-1}, representing the average value of raw cane harvested from the first to the sixth cut.

The production unit fleet was composed of 23 sugarcane harvesters, all suitable for harvesting crop lines spaced in 1.50 m. These harvesters had of lifespan ranging from 1 to 4 years, with different quantities of worked engine hour and elevator hour.

The employed machines presented the following technical characteristics: engine 6090T Power Tech (Tier III), with 9.0 liters, of 251 kW (336 hp), with four valves per cylinder, equipped with Field Cruise system, of engine rotation control and gauge belt wheels set of 1.88 m. These harvesters did not present automatic conduction system (autopilot - GNSS) during the operation and worked on an average speed range of 3 to 6.0 km h^{-1} for the period of harvesting, with the greatest speed used to attend feedstock demands of industrial unit, aiming to deliver greater quantity of plant load in the shortest time interval, when necessary.

The experimental design was established according to quality control analyses, with the harvesting loss monitoring conducted on a daily basis in harvested areas, over a period of 70 days, after the beginning of 2014 harvest. The sampling values were collected through a control system of plant loss that had daily field collection throughout the operation.

The loss evaluations were conducted by two crews of five people, collecting samples in five harvest teams, with each of them containing three to five harvesters. Each machine counted on one to two people, previously trained for collection and quantification of each type of loss. At the end of the evaluation period, 194 sampling points were collected in total, for each type of analyzed loss (demonstrated by the 'x' axis on figures). It is highlighted that, in the days when the machines did not work, for maintenance reasons, unfavorable climate conditions, and/or maintenance of sugarcane processing industrial areas, these were not measured or quantified.

Finally, the quality analysis was carried out from these sampled points, and then the control chart models per variables were produced, enabling to analyze, interpret and diagnose actions of possible special causes throughout the harvesting, as well as to report or not process stability, aiming operation improvement.

The losses in sugarcane mechanical harvesting were monitored for each sample, through a metallic frame of 10 m^2 (3.33 x 3.00 m), with the last transversal value directed towards the harvest. All measured losses were evaluated only during daytime harvesting operations. The sampling area was set right after harvester passing, in which loss types were manually collect, and subsequently separated in batches and weighted, in scales of 0.1 g precision, according to methodology described by NEVES et al. (2004).

The sugarcane mechanical harvesting losses were divided in accordance with the analysis criteria adopted on a daily basis by the production unit, as follows: full grinding wheel, stem fraction (wheels) with characteristic cut of harvesting knife or of base cut, in both ends; Stumps: rooted stem fraction cut above soil surface, with length varying from 0.05 to 0.14 m; Fixed piece: stem fractions greater than ≥ 0.15 m, that must be necessarily attached to the soil; Whole cane: stem fraction equal or superior to 2/3 of its average length, with such value estimated near the sampling place and stem attached or not to soil by roots; Chips: smaller-sized stem fragments, lacerated or not; Loose piece: variations of stem fractions, that do not fit within loss definitions of full grinding wheel, whole cane, fixed piece, stump and chips; and Total losses: all previously mentioned stem fractions, adding each loss type until reaching the total accumulated value.

As initial analysis, data were submitted to descriptive statistics in order to allow general visualization of data performance. This analysis assumes the values as independent among themselves, therefore, without considering the influence of sampling place and the relative positions. Lastly, the general demonstration of data performance was carried out by calculating central tendency measures (average) and dispersion measures (standard deviation and variance coefficient). The data normality was verified through the Ryan-Joiner test, with a proximity measure of the points and the line estimated in probability, granting greater severity to the analysis (NOIMAN et al., 2013).

The individual values charts must be implemented in order to monitor variables or quality indicators that influence quality of the items or of the process over time that in this situation is applied in mechanized farming operations, specifically in monitoring losses derived from sugarcane mechanical harvesting.

MONTGOMERY (2009) defines the general average of individual values according to equation 1, in where:

$$\mu = \frac{n_1 + n_2 + n_3 + \ldots + n_i}{n_t} \tag{1}$$

In which,

μ: Individual values average;

n: Sampling point value,

n_t: Total number of observations.

The control limits of individual value charts can be calculated using eqs. (2) and (3):

$$\text{UCL} = \mu + \text{L}.\sigma \tag{2}$$

$$\text{LCL} = \mu - \text{L}.\sigma \tag{3}$$

In which,

UCL: Upper control limit;

LCL: Lower control limit;

μ: Individual values average;

σ: Standard deviation,

L: Range between average and control limits.

The control charts of individual values were calculated using the range between average and control limits, with the value 3 (three) randomly chosen for analysis. Such value was elected in accordance with recommendations by MONTGOMERY (2009), once it enables better evaluation results, without under or overestimation of value quantity (samples) above control limits.

However, this control chart model is not capable of detecting minor variations throughout the process, only higher-magnitude dissimilarities, thus the process can be incorrectly identified when data set does not present normal distribution of probability.

The control chart of moving average, according to MONTGOMERY (2009), is represented by individual values and the moving average coverage (w) stipulated due to the rigorousness to be implemented in the analysis. The number of presented individual values corresponds to the value of moving average coverage. From this observation, the individual values are substituted by the moving individual values average, calculated in accordance with [eq. (4)]:

$$\beta = \frac{n_i + n_{i-1} + n_{i-2} + \ldots + n_{i-w+1}}{w} \tag{4}$$

In which,

β : Moving average of individual values;

n_i: Sampling point value,

w: Moving average coverage.

The control limits of moving average charts can be calculated using eqs. (5) and (6):

$$\mathrm{UCL} = \mu + \frac{3\sigma}{\sqrt{w}} \tag{5}$$

$$\mathrm{LCL} = \mu - \frac{3\sigma}{\sqrt{w}} \tag{6}$$

In which,

UCL: Upper control limit;

LCL: Lower control limit;

μ: Moving average of individual values;

σ: Standard deviation,

w: Moving average coverage.

For this analysis, a moving average coverage of value three (w=3) was established in order to obtain a better result level, not affecting the quality of analysis (MONTGOMERY, 2009). Nevertheless, this control chart model, in a similar way to the individual values ones, potentially requires normality assumption of data set for its creation; therefore, the moving average is more efficient at detecting minor process variations compared to the Shewart chart.

The control chart models in which the exponentially weighted moving average (EWMA) is used, also called advanced control graphs, are improved Shewhart graphs, developed for specific situations, in which it is aimed to minimize simultaneously the occurrence of points outside the control limits (false alarm) and not visible alarms (AMIRI & ALLAHYARI, 2011), in virtue of its greater analysis rigorousness.

MONTGOMERY (2009) defines the exponentially weighted moving average (EWMA) according to [eq. (7)], where:

$$z_i = \lambda . \sum_{j=1}^{i-1} (1-\lambda)^j . x_{i-j} + (1-\lambda)^i . z_0 \tag{7}$$

In which,

z_i: Weighted moving average value;

i: Measured characteristic value;

z_0: Process target average;

ë: Rigidity factor of analysis,

j : 1, 2, 3,..., i. (samples).

The upper and lower control limits that constitute the exponentially weighted moving average can be calculated through eqs. (8) and (9), respectively:

$$UCL = \mu + L.\sigma.\sqrt{\frac{1}{(2-\lambda)}.[1-(1-\lambda)^{2i}]} \tag{8}$$

$$LCL = \mu - L.\sigma.\sqrt{\frac{1}{(2-\lambda)}.[1-(1-\lambda)^{2i}]} \tag{9}$$

In which,

UCL: Upper control limit;

LCL: Lower control limit;

μ: General average;

L: Range between average and limit;

σ: Standard deviation;

ë: Rigidity factor of analysis,

i: 1, 2, 3,...,. (Samples).

The control charts of exponentially weighted moving average were calculated using the range width between average and control limits, with the value 3 (three) and the analysis rigidity factor chosen as λ=0.4. Such value was chosen based on MONTGOMERY (2009) recommendation, who suggested using (λ=0.4) when range width with value 3 (three) is used. It is also highlighted that, this tool does not require data normal probability of distribution in order to monitor processes and the values to be employed in mechanized farming operations are still not specified in bibliography.

RESULTS AND DISCUSSION

The quality indicators of sugarcane mechanical harvesting (Table 1) cannot be defined by the normal probability density function according to the Ryan-Joiner test, describing non-normal distributions for the data set. The non-normality for all types of losses can also be supported by the high value of the Ryan-Joiner test, which presented values distant from zero (OZTUNA et al., 2006).

TABLE 1. Normal probability distribution test and parameters of descriptive statistics for losses resulting from sugarcane mechanical harvesting (Mg ha^{-1}).

Quality indicators	$\bar{X}$	σ	VC	RJ	p-Value
Full grinding wheel	0.61	0.36	58.98	4.32	<0.005^{A}
Stumps	0.23	0.25	109.58	9.50	<0.005^{A}
Fixed piece	0.19	0.17	89.31	7.04	<0.006^{A}
Whole cane	0.46	0.52	114.75	12.09	<0.005^{A}
Loose piece	0.14	0.15	111.55	16.42	<0.004^{A}
Chips	0.54	0.37	68.36	5.77	<0.005^{A}
Total losses	2.19	1.28	58.38	6.09	<0.005^{A}

$\bar{X}$ – General average (Mg ha^{-1}); σ – standard deviation; VC (%) – variance coefficient; RJ – normality values of Ryan-Joiner test; p-Value – probability distribution value (p>0.05); N –normal probability distribution; A – non-normal probability distribution.

On the other hand, the highest and the lowest standard deviation values were achieved for total losses and loose piece, respectively, while the highest variance coefficient was verified for whole cane and the lowest for total losses. JONES et al., (2011), reported that variance coefficients comparable to the ones found in this study, are classified as high, characterizing great variability of data set over sampling period.

As a final point, the high variability derived from this dynamic process, noticeable through descriptive statistics (dispersion measures of data set), potentially, compromise the loss indexes during sugarcane mechanical harvesting, diminishing the operation quality level.

The full grinding wheel loss-type presented process instability for the three control chart models, with points above the upper control limit, describing presence of special causes extrinsic to the operation, acting during the sugarcane harvest (Figure 1a, 1b e 1c), representing 28% of total losses. The possible special cause might be attributed to the lack of synchronism between the haulouts and harvester set, causing greater loss levels in these places, with such levels being associated with the human factor, which means, the inability of the operator to maintain alignment between machines, during the harvest of sugarcane lines, once they did not use autopilot.

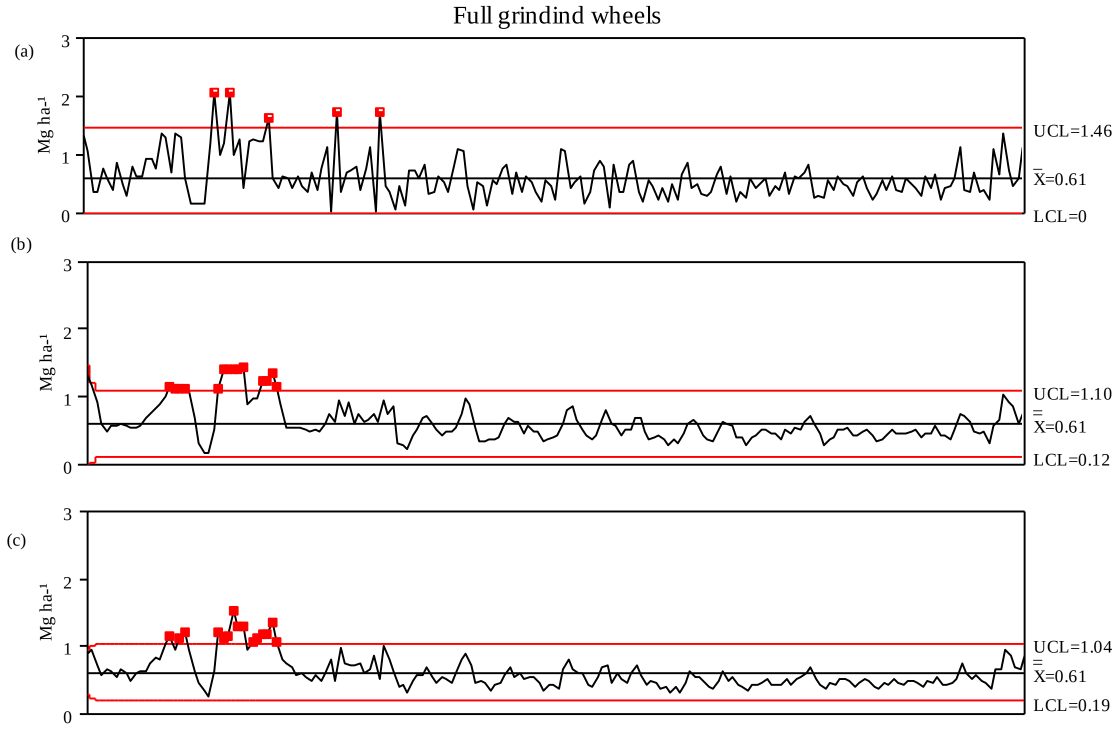

FIGURE 1. Full grinding wheel losses in sugarcane mechanical harvesting. (a) Control chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\bar{X}$ and $\bar{\bar{X}}$: General average of individual values.

The process instability is demonstrated by the three tool types of statistical process control, in which the number of observations above the upper limit, common to the three charts, occurs in numbers of three, once if any control chart was used in these sampling places, the process would be considered unstable.

When comparing points outside the limit for control charts of individual values, moving average and exponentially weighted moving average, it is verified that these reach 5, 15, 14 points, respectively. This result indicates that the chart of individual values did not present a quantity of points outside control (false alarms) greater or next to the exponentially weighted moving average values, which was different from information found in the literature about quality control (MONTGOMERY, 2009).

Regarding stump loss-type, the sugarcane harvesting process was diagnosed as unstable for the three used chart model, resulting in 11% of total losses (Figure 2a, 2b and 2c). The possible points outside the control limits can be explained by the basal cut mechanism oscillation during harvesting. It is caused by operator inability at contmoving the harvester, by the non-use of automatic control of height cut and by the land oscillation during harvesting, with these situations attributed to special causes: labor, machine and environment (land declivity and soil preparation), respectively.

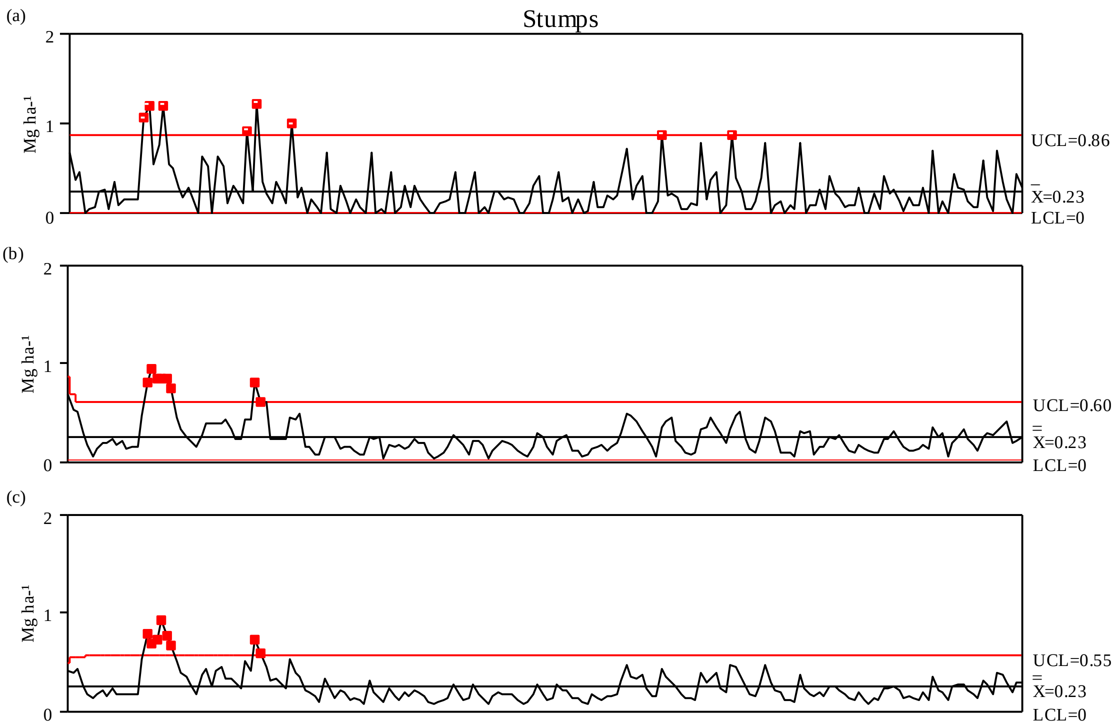

FIGURE 2. Stump loss-type in sugarcane mechanical harvesting (a) Control Chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\bar{X}$ and $\bar{\bar{X}}$: General average of the individual values.

The total points outside the limit for control charts of individual values, moving average, and exponentially weighted moving average was of 9, 8, and 8, respectively. It describes that, for this quality indicator, the normality assumption might not be a major factor for choosing the chart model for quality analysis, by charts of individual values and of moving average, due to proximity and quantity of points outside control.

It is still observed that, when analyzing models of moving average and of exponentially weighted moving average, all the points outside control are equivalent, in other words, the estimate of this type of loss level can be conducted through moving average chart, independently from normality assumption, describing variations only in the estimated values of average and not between the samples. VOLTARELLI et al. (2013), when using individual values charts to monitor performance of farm tractor in sugarcane planting, reported that these demonstrate great importance at analyzing operation quality, reflecting on detection of points that extrapolate control limits. Such result supports the improvement plan to be implemented, for subsequent operations, once such situation can also be associated with the present study, aiming to increment its quality level.

Regarding the fixed piece indicator in sugarcane harvesting, the process was unstable for the three chart models, describing 8.6% of total losses (Figure 3a, 3b and 3c). This instability can be attributed to special causes – labor, environment, and machine, possibly explained by oscillation of the basal cut mechanism during harvesting, by the inability of the operator at contmoving the machine or by the harvester high speed and land wavering during harvesting, respectively.

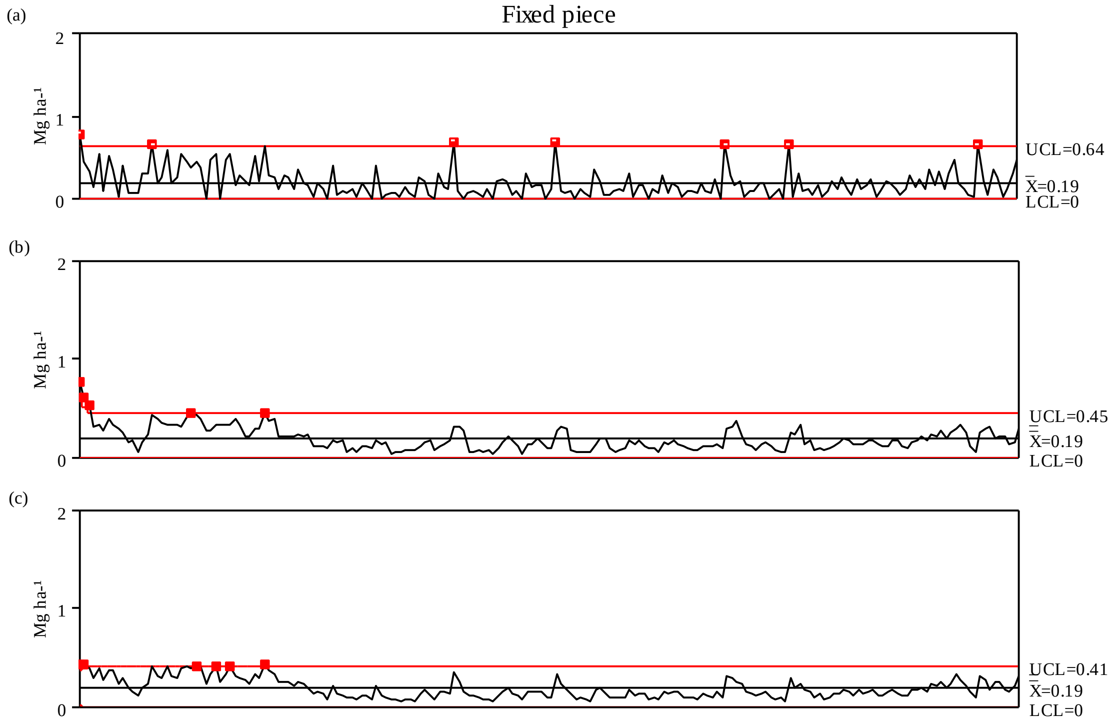

FIGURE 3. Fixed piece loss-type in sugarcane mechanical harvesting. (a) Control chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\overline{X}$ and $\overline{\overline{X}}$: General average of individual values.

The individual values chart, moving average and exponentially weighted moving average presented 7, 5, 5 points that extrapolate the upper control limit, respectively. However, it is further noted that the variability between control chart limits of exponentially weighted moving average is lower than the others, which demonstrates greater rigorousness of this quality tool model.

However, when comparing the chart of individual values against the moving average, which require normal probability distribution, those present an equivalent point, more specifically, outside the control limits. This situation defines that, due to the higher level of rigorousness of the moving average, using the average of the three last sampling values as assessment base, non-visible false alarms might occur throughout the process, since the loss level quantification of this average value is estimated. According to Segundo YANG et al. (2013) the efficiency of moving average charts at monitoring and analyzing process instability, when data present non-normal distribution, once this fact presents similarities with this study, as the monitoring of sugarcane losses is also conducted in this condition.

The process instability for the whole cane loss-type can be verified through control charts (Figure 4a, 4b and 4c), in which there might be non-random causes extrinsic to operation interfering in its quality level. The points outside control limit can be related to the feedstock factor associated with the environment, referring to greater quantity of lying-down sugarcane attributable to its own genetic characteristics or caused by wind action, inhibiting sugarcane gathering through the lifter mechanism of harvester.

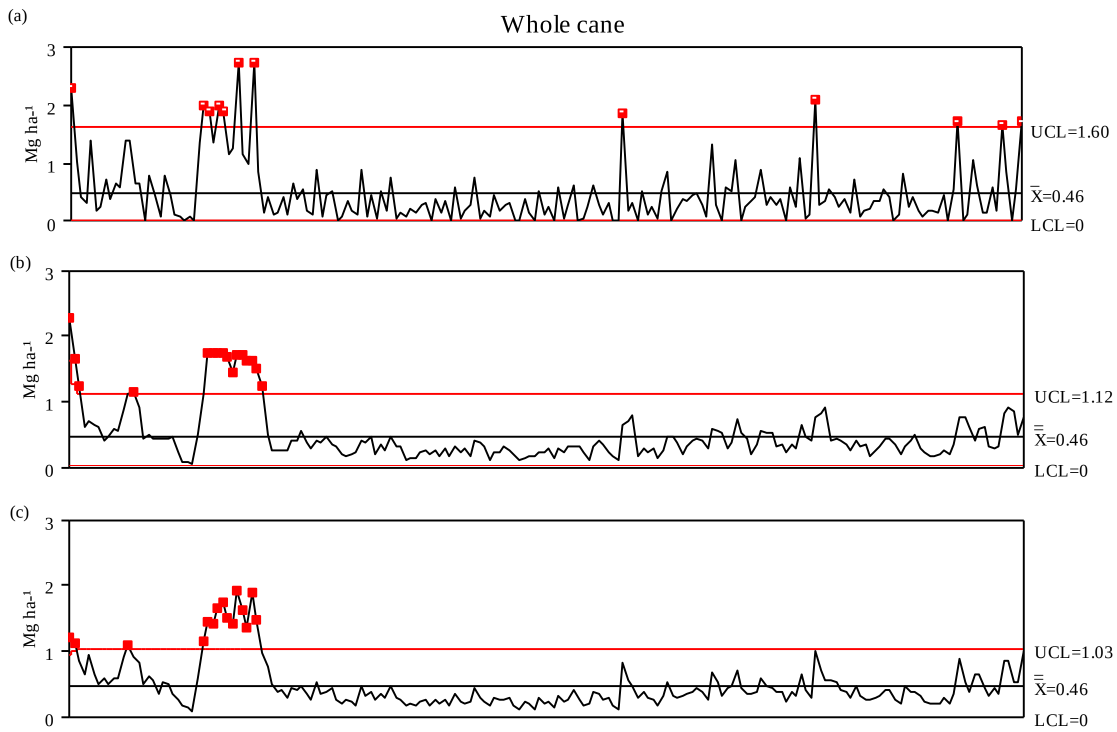

FIGURE 4. Whole cane loss-type in sugarcane mechanical harvesting. (a) Control chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\bar{X}$ and $\bar{\bar{X}}$: General average of individual values.

On the other hand, the machine factor associated with labor might be acting there, due to increased harvester operating speed, which results in inefficient gathering of the sugarcane to be harvested, and thus boosting this loss index, which represented 21% of total losses. When assessing losses in sugarcane mechanical harvesting, MOONTREE et al. (2012) reported that the whole cane is least lost in the lowest operating speed of harvester, influenced by sugarcane gathering inefficiency by the harvester platform. Once this fact did not occur during sugarcane mechanical harvesting of this study, which evidences quality of this operation for this quality indicator.

Independently from normality assumption of control charts, the three applied models displayed points outside control, which is potentially an indicative that any chart model can be used for this analysis. Nevertheless, when the individual values chart (Figure 4a) is compared to the others, this shows points outside control at the final sampling period, a contrasting situation due to the foundation to quantify real loss values.

The control charts of individual values, moving average and exponentially weighted moving average displayed unstable process, resulting in 7, 8 and 9 points above the upper control limits (Figure 5a, 5b and 5c), respectively, for chips loss-type in the course of harvesting. The average loss for this quality indicator represents approximately 25% of total losses.

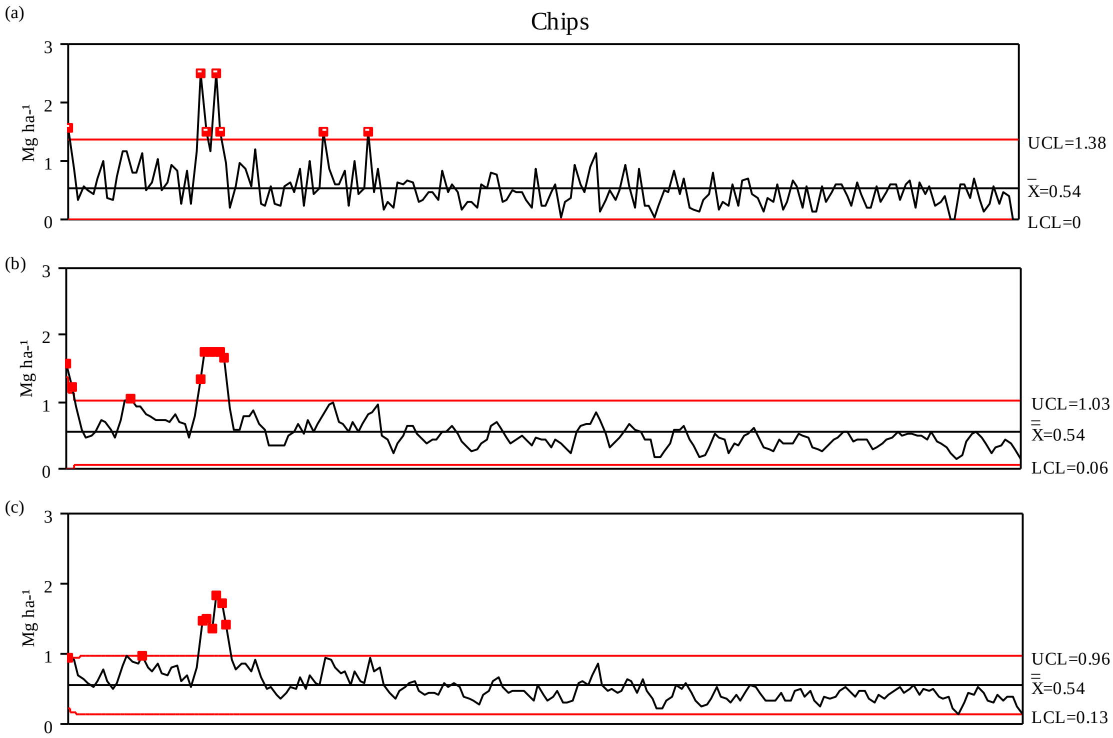

FIGURE 5. Chips loss-type in sugarcane mechanical harvesting. (a) Control chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\bar{X}$ and $\bar{\bar{X}}$: General average of individual values.

The chips loss-type is mainly influenced by stem fractioning into pieces that are smaller than the expected, carried out by a harvesting knife, associated with exhaustion speed of primary extractor, and due to pricking of central base cut in stems attached to soil and in harvested stem. MANHÃES et al. (2014), when estimating sugarcane mechanical harvesting in different operating speeds, reported that chips and/or shrapnel loss-types did not present differences in virtue of this factor, however, their values were similar to the ones found in this study.

In spite of the instability presented by the three chart models for chips loss-type, when the process is analyzed as a whole, the quantity of points outside control among charts can be considered irrelevant attributable to the number of samples and the variability of this quality indicator. Accordingly, any of the three models of could be used to monitor these losses, independently from normality assumption, once the situation analyst understands the process and knows how to identify if the situation is serious or not, in order to improve it, if necessary.

The loose piece average loss represents 6% of total losses, once this can be caused by the harvesting knife cut, when these knives cut the stems into smaller fractions, characterizing in up to two internodes, with possible shattered ends (Figure 6a, 6b and 6c), and this process is considered unstable for this quality indicator, independently from the quality tool used.

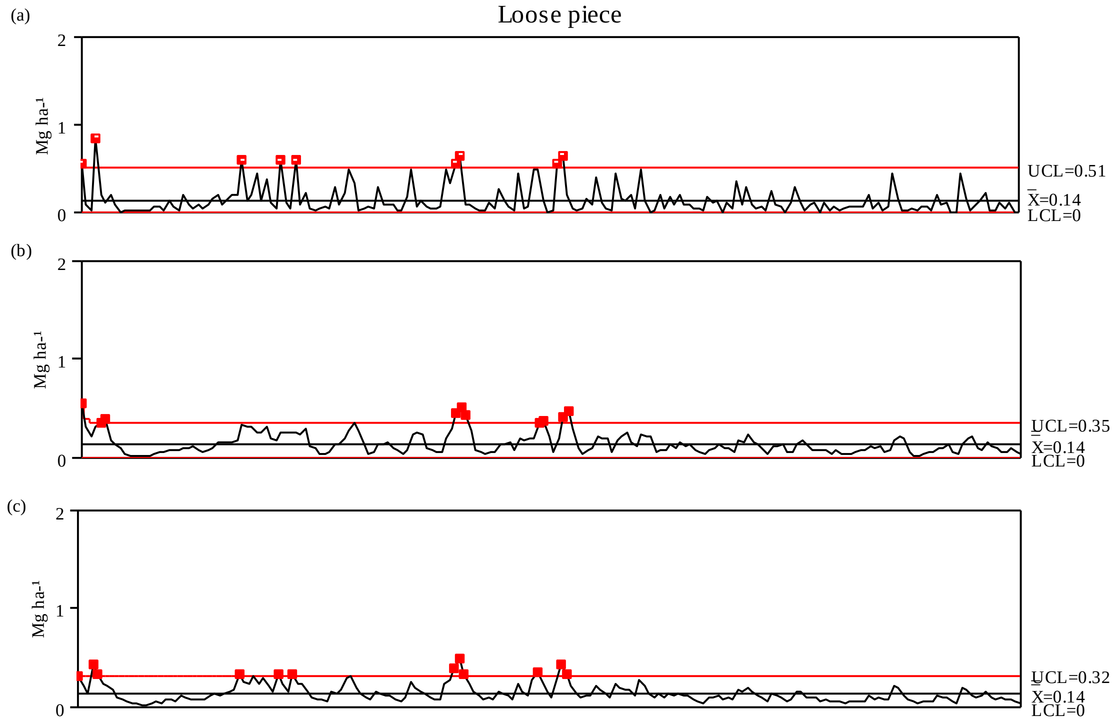

FIGURE 6. Loose pieces loss-type in sugarcane mechanical harvesting (a) Control charts individual values, (b) Moving average, (c) Exponentially weighted moving average. $\bar{X}$ and $\bar{\bar{X}}$: General average of individual values.

It is also perceived that only five points outside control limits are equivalent for the three control chart models, a situation that portrays the quantity variation of points outside or not the calculated limits, attributable to the assessment base of each analysis, given that the exponentially weighted moving average presented a total of 12 points above the upper limit. CHAKRABORTY & KHURSHID (2013) when evaluating probability of occurring greater quantity of points above the upper control limit, by virtue of non-normality of data distribution, for individual values chart, reported that using short sampling sequences can be an alternative to monitor processes, a situation that did not occur in this study.

Regarding total losses in sugarcane mechanical harvesting, there was process instability for the three control charts (Figure 7a, 7b and 7c), which characterizes a sum of all the previously cited loss-types, representing 2.7% of losses compared to average productivity of evaluated period.

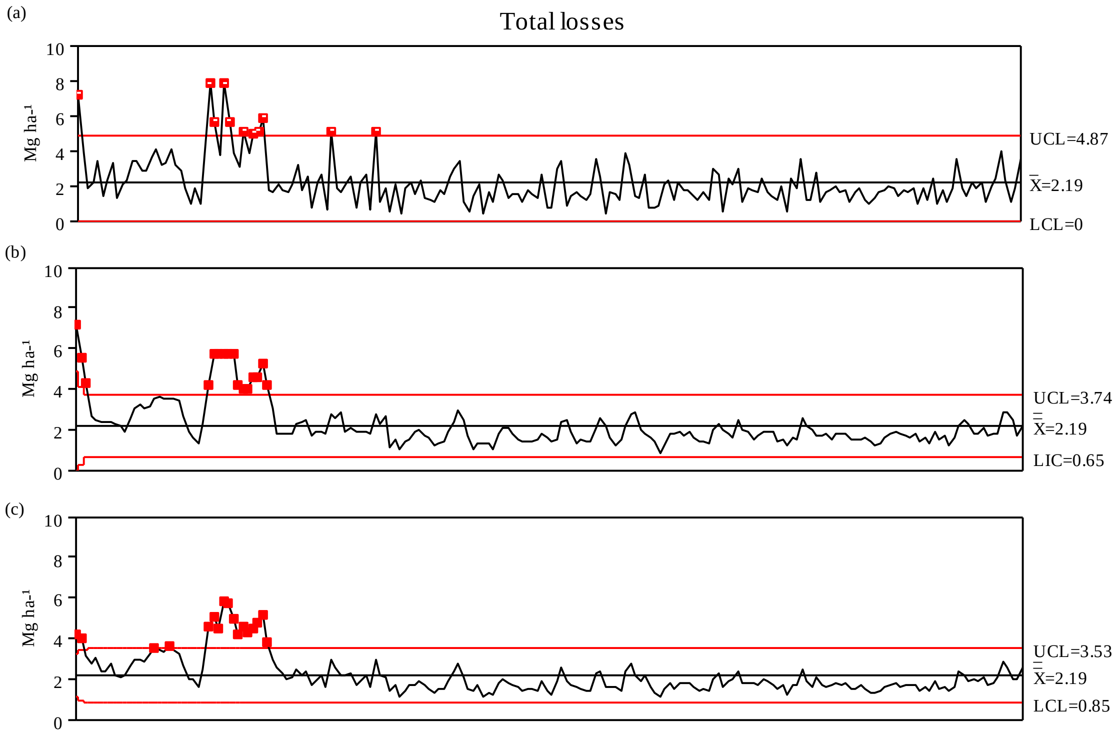

FIGURE 7. Total losses in sugarcane mechanical harvesting. (a) Control Chart of individual values, (b) Moving average, (c) Exponentially weighted moving average. $\overline{X}$ and $\overline{\overline{X}}$: General average of individual values.

The variability level of total losses from sugarcane mechanical harvesting can be considered high, independently from normality assumption of the data set. For this reason, the use of a more rigorous control chart might not aggregate great improvements and quality to the process. The situation would be different if this condition presented a low sampling variability (Table 1). According to LEE et al., (2014) the exponentially weighted moving average has greater robustness compared to the Shewhart charts and the moving average, in a situation of lower variability, a condition that can be similar to what occurred in this study, in which the data are non-parametric.

CONCLUSIONS

The control chart of individual values is the best option to monitor losses in sugarcane mechanical harvesting as it produces results more easily, compared to the others.

The exponentially weighted moving average chart demonstrates higher quantity of points outside control limits, with exception of the quality indicators stump and fixed piece loss-types, compared to the other two models of control charts.

Independently from normality assumption, the charts of individual values and of moving average exhibit full potential at monitoring losses in sugarcane mechanical harvesting.

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