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Agronomic capability of mechanized sugarcane planting

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Abstract

The capacity of the mechanized planting of sugarcane to keep the quality standards (mills) is very difficult to be achieved. The external sources of variation make it difficult to be maintained inside the acceptable level over time. Thus, the goal of this study was to evaluate the agronomic performance of mechanised sugarcane planting in two operation shifts using statistical process control. Mechanised planting was performed in an agricultural area state of São Paulo, Brazil. The experimental design was completely randomised with a total of 80 sampling points (replicates), 40 replicates for daytime operation and 40 replicates for night-time operation. The performance of the mechanised set for both operation shifts was evaluated using the following variables and/or quality indicators: number of billets m^{-1}, total number of shoots m^{-1}, number of viable shoots m^{-1}, percentage of viable shoots, and seedling consumption (Mg ha^{-1}). The results showed that the operational quality of mechanised sugarcane planting varied between the day and night shifts. The total number of shoots m^{-1} exhibited higher variability for the night than for the day shift. All analysed quality indicators of mechanised sugarcane planting were considered not capable (Cp and Pp < 1.33) of meeting the established targets for the day shift, regardless of the process stability.

Keywords: statistical process control; agricultural machinery; agronomic performance, *Saccharum* spp.

Abbreviations: UCL_upper control limit; LCL_lower control limit; $\bar{X}$_individuals average; $\overline{M}\bar{R}$_moving range average; σ_standard deviation; AD_value of the Anderson-Darling normality test; p-Value_probability distribution value; GNSS_Global navigation satellite systems; LSL_lower specification limit; USL_upper specification limit; Cp_Process capability index; CPL_Process capability index relative to lower specification limit; CPU_Process capability index relative to upper specification limit; Cpk_Minimum process capability index; Pp_Process performance index; PPL_Process performance index relative to lower specification limit; PPU _Process performance index relative to upper specification limit; Cpm_Process capability index relative to target.

Introduction

The sugar-alcohol agricultural industry is important both nationally and internationally due to investments in new mechanisation technologies. The goal is maximising the industry's expansion through government incentives and/or rural credit, as well as due to economic and social questions associated with the cycles of these rural activities (Rípoli and Rípoli, 2010; Rípoli, 2007).

Mechanised sugarcane planting should aim for the sustainability of the industry to increase average productivity and operational quality. Previous studies of mechanised sugarcane planting have been performed primarily for night-time operation, and few studies have been published for the daytime operation shift. Due to the scarcity of studies, the use of statistical process control tools becomes essential for the monitoring of this process. Such monitoring contributes to the detection of eventual special causes of variation and to the creation of improvement plans with the goal of eliminating the influence of extrinsic causes of variation, which will result in increasing operational quality through the decrease in variability (Voltarelli, et al., 2013).

To achieve high quality levels in operation cycles with agricultural machinery, which leads to high variability, quality control programs must be established in the sugarcane units and mills. These programs would help to improve the operational quality in the short term and primarily contribute to the long-term goal of reducing variations due to climate, labour, machinery, raw material, and other factors (Barros and Milan, 2010).

The financial response or increase in productivity may not be very clear when first implementing quality improvement planned. However, it may become clearer over time, because the monitoring and improvement of operation performance are continuous (Voltarelli et al., 2013). Peloia et al. (2010) used statistical process control, namely control charts and process capability analysis, to analyse the mechanical cut of sugarcane billets during harvest. The authors diagnosed the process stability using control charts and capability plots and concluded the process to be not capable of reaching short- or long-term satisfactory results for either burnt or green sugarcane. Milan and Fernandes, (2002) evaluated the quality of soil preparation operations, namely scarification and harrowing, using statistical process control. They observed that the establishment and subsequent performance of an improvement plan was efficient in increasing the quality of operations and that this was only possible due to the decrease in variability of the operation and of the set targets.

Cassia et al. (2013) evaluated the quality of mechanised harvested coffee in a circular planting system using control charts and observed high variability resulting from losses and damage to plants. This result can be considered common in mechanised agricultural operations, becuase it does not result in losses and decreased quality of the operation. The authors

further reported that the sampling points (replicates) remained within the control limits. They noted that the process to be stable. Additional reports on the use of quality tools in studies of mechanised agricultural operations have been published with the goal of increasing the quality of operations by decreasing intrinsic and extrinsic variability to reach satisfactory capability indices (Compagnon et al., 2012; Noronha et al., 2011; Salvi et al., 2007; Suguisawa et al., 2007). However, these authors did not analyse process capability. Therefore, these types of analysis are scarce to sugarcane crop mechanisation (Reis, 2009).
Considering the hypothesis that variability from the mechanised sugarcane planting operation may affect the process capability, in both the short and long terms, the goal of this study was to evaluate the capability of the mechanised sugarcane planting operation during the day and night shifts using statistical process control.

Results

Normality test and descriptive statistics parameters

The quality indicators of mechanised sugarcane planting used for the process capability analysis were chosen based on their meeting with the assumption of normality of distribution ($p>0.05$) (Table 1). According to the Anderson-Darling normality test, the quality indicators number of billets, total number of shoots, number of viable shoots, percentage of viable shoots m^{-1}, and seedling consumption (Mg ha^{-1}) exhibited normal distributions ($p>0.05$) for both daytime and night-time operations. For both operation shifts, the total number of shoots and number of billets m^{-1} exhibited the highest and lowest standard deviations, indicating high and moderate dispersion, respectively. Table 1. also shows that the number of viable shoots m^{-1}, percentage of viable shoots m^{-1}, and seedling consumption Mg ha^{-1} exhibited higher standard deviation for the night than for the day shift. This result may indicate higher variability for the night shift due to the mechanised sugarcane planting displaying high intrinsic (e.g., cultivars suitable for harvest and mechanised planting, number of shoots $billet^{-1}$) and extrinsic (e.g., labour, environment, harvest, seedling transport and loading, process monitoring frequency and method, impacts and damage suffered by seedlings during the planting system) sources of variation.

Individuals and moving range control charts

Individuals and moving range control charts for the mean number of billets show the stability of the process for the daytime and night-time operation shifts (Fig. 1a and 1b). This stability is consistent as all observations were between the lower and upper control limits for both charts. On the other hand none of the four types of errors were detected, indicating that only natural factors are acting during the process. Moreover, the higher variability of this quality indicator was not significant for the day shift. For the quality indicator such as mean number of total shoots, the process was within the upper and lower control limits both for the individuals and for the moving range control charts, on both operation shifts, and therefore, was considered as stable (Fig. 2a and 2b). The presence of random causes of variation can indicate that the variation of values and/or observations around the mean was due to common causes of variability that are intrinsic to the process. The highest variation was observed for the night operation shift in contrast to the observation for the mean number of billets (Fig. 2b). For the average number of viable shoots, only common causes of variation intrinsic to the process were observed over time, with the observations not varying greatly from the overall and moving range averages (Fig. 3a and 3b). Similar to the mean total number of shoots, the highest variability of this quality indicator was also observed for the night shift. For the mean percentage of viable shoots, special causes of variation (extrinsic to the process) were not detected, due to the action of common causes of variation (intrinsic to the process), which was evident in the individual and moving range control charts (Fig. 4a and 4b). The action of common causes of variation observed for this quality indicator was higher for the day than for the night shift (Fig. 4a) due to the higher standard deviation, indicating higher value dispersion resulting in a greater distance of the upper and lower control limits from the overall mean observed in the individuals control chart. It should be noted that the variation of data relative to the control limits for the individuals control chart, which is calculated using the standard deviation of the mean. Thus, errors in the interpretation of these results can occur if this parameter alone is used for the real process variability, which would be detrimental for managerial decision making. The solution is to always use and interpret moving range control charts because their deviations are calculated based on the mean sum of the differences between individual observations; therefore, constituting a more accurate measure. For seedling consumption, only common or random causes of variation were observed for the individuals and moving range control charts for both operation shifts (Fig. 5a and 5b). A slight variation of the control limits was also observed on both charts, being higher for the day shift. In general, seedling consumption alternated between the highest and lowest variability depending on the daytime and night-time operation shifts. However, this alternation may influence the process and can decrease its pre-determined quality level, even slightly. Monitoring is essential to increase the process quality and to achieve the large-scale production of items or products without ceasing to meet the required specifications. The reason is that it increases the number of samples over longer time intervals and/or decreases the evaluation time of the variables; thus, acquiring a higher number of samples in a shorter period of time. Because the two analyses met assumptions 1 and 2 (normal distribution and stability, detected in individuals and moving range control charts, respectively), the process capability was determined, which enabled the assessment of whether the operation was capable of meeting the specifications of the sugarcane mechanised planting operation, within USL and LSL, in the short and long terms.

Analysis of capability of sugarcane mechanised planting

Day shift

For the quality indicator (number of billets m^{-1}) during the day shift, the considerable distance between the potential and overall distribution curves may indicate that the process is not centred on the target. This possibility is indicated by the difference between Cp (Process capability index) and Cpk (Minimum process capability index), and Cpm (Process capability index relative to target) (Fig. 6). The process's observed performance revealed the production of items or observations outside the specification limits (USL and LSL) with only 45% of the values within the specification limits. However, the capability indices (Cp, Cpk, and Cpm) had to be below the specified minimum acceptable level (1.33) for the process to be considered capable of producing results within the specification limits, in the short and long term periods. The Cp and Cpm (0.25 and 0.14, respectively) can be considered to be close to each other, but Cpk (-0.07) was lower, confirming that the process was not centred and was not capable. The negative Cpk value indicates that the overall

Table 1. Normality test and descriptive statistics for mechanised sugarcane planting for the two operation shifts evaluated.

Quality indicators	Day shift				Night shift			
	Average	σ	AD	p-Value	Average	σ	AD	p-Value
Number of billets m^{-1}	15.7	2.83	0.346	0.465	15.2	3.84	0.570	0.131
Total number of shoots m^{-1}	37.0	8.58	0.385	0.376	35.0	9.38	0.492	0.207
Number of viable shoots m^{-1}	23.6	5.08	0.290	0.594	23.3	6.62	0.339	0.483
% of viable shoots m^{-1}	63.9	4.33	0.203	0.867	65.9	5.02	0.705	0.061
Billets consumption (Mg ha^{-1})	24.0	5.85	0.346	0.465	23.2	5.87	0.570	0.131

σ – standard deviation; AD – value of Anderson-Darling normality test; p-Value – probability distribution value.

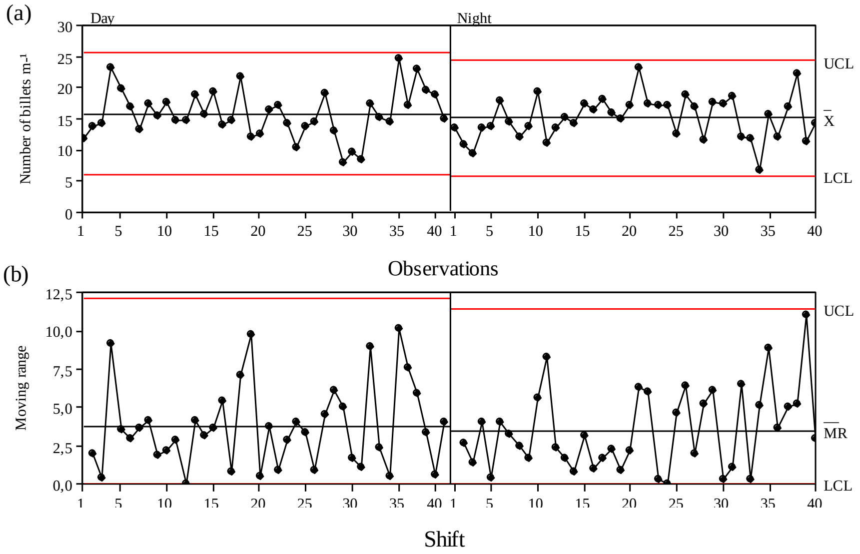

Fig 1. Control charts for mean number of billets in mechanised sugarcane planting. (a) Individuals control chart. (b) Moving range control chart. UCL: Upper control limit. LCL: Lower control limit. $\bar{X}$: Individuals average. $\overline{MR}$: Moving range average.

Table 2. Control specification limits used in the mechanised sugarcane planting operation for the day and night shifts.

Quality indicators	Lower specification limit (LSL)	Target	Upper specification limit (USL)
Number of billets m^{-1}	10	13	15
Total number of shoots m^{-1}	25	35	45
Number of viable shoots m^{-1}	18	20	23
Viable shoots (%)	60	85	90
Billets consumption (Mg ha^{-1})	13	19	25

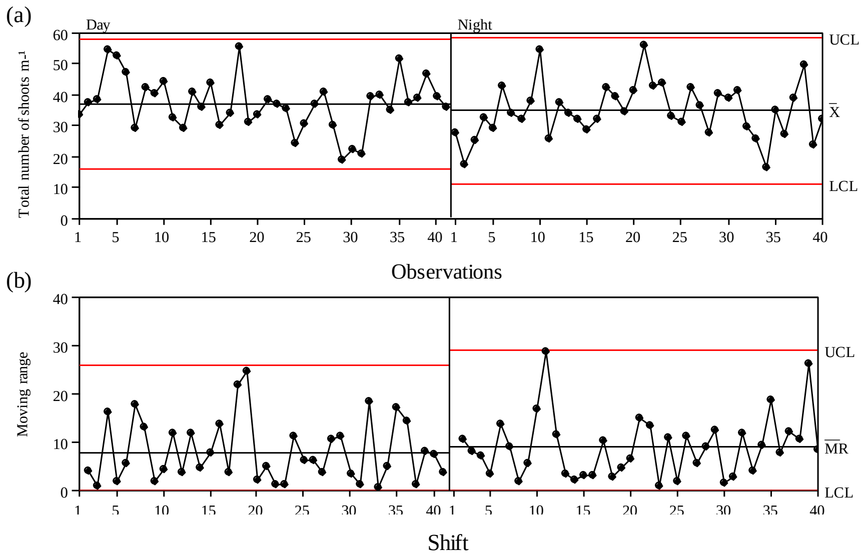

Fig 2. Control charts for mean number of total shoots in mechanised sugarcane planting. (a) Individuals control chart. (b) Moving range control chart. UCL: Upper control limit. LCL: Lower control limit. $\bar{X}$: Individuals average. $\overline{MR}$: Moving range average.

mean (15.71) was outside the specification limits. More specifically, in the present case, it was above USL.

The capability indices relative to USL for the overall (PPU) and potential (CPU) process performances (-0.06 and -0.07, respectively) exhibited negative values, indicating that mean to be closer to USL than to LSL. This resulted in a decreasing capability index towards the right side of the histogram. These results from Ppk and Cpk were calculated using the smaller index as a precaution, as we want to use only the best values.

However, 64.18% of the observations of the overall process performance were outside the specification limits, calculated based on the intrinsic (random) and extrinsic (non-random) causes of variation. Eliminating the extrinsic sources of variation (non-random), i.e., considering only the random causes, 62.69% of the observations were outside the specification limits, also a high value. The investigation of these causes; therefore, was not completely viable. For the total number of shoots m^{-1} in day shift, the process was considered not capable of producing satisfactory items in the short and long terms because Cp and Pp were lower than 1.33 (regardless of the closeness of the Cpm and Cpk indices) (Fig. 7). The analysis of the overall process performance revealed that 25.81% of the observations were outside the specification limits, considering both common and special causes of variation. When special causes are excluded from the analysis, up to 82.54% of the observations were within the specification limits, according to the potential process performance, which nonetheless may not make the process capable of meeting the specification limits. Moreover, the overall and potential capability indices relative to the lower specification limit (CPL and PPL, respectively), were higher when compared to the indices relative to the upper limit (CPU and PPU), indicating a higher process capability index on the left side than on the right side. The behaviour of the overall and potential distribution curves for number of viable shoots m^{-1} in day shift indicates that the process was not centred on the target. This information was confirmed by the distancing between the Cp (0.21) and Cpk (-0.06) indices and by the value of Cpm (0.11). Therefore; the process was not to be capable of producing results in the short (Cp 0.21) and long (Pp 0.16) terms, which may be explained by the high value of the observed performance outside the specification limits (65.00%) (Fig. 8). The analysis of the observed performance revealed that 55.00% of the observations were above USL, which may have determined the displacement of the process mean to values above USL. This result was confirmed by the negative Cpk (-0.06) and Ppk (-0.04) indices and by the relationship between the potential capability (CPU) and the overall capability (PPU) relative to the upper specification limits (-0.06 and -0.04, respectively). The overall process performance indicates that only 31.52% of the produced items evolved from natural and non-natural process variation within the specification limits. When the same comparison is performed for the process capability, for which only the natural causes of operation variation are considered, 35.62% of the observations are within the specification limits, and eliminating the natural causes of variation is not feasible economically. For the day shift, the process capability as a function of the percentage of viable shoots was potentially capable of meeting the specification limits in the short and long terms. However, to meet these specifications, the special causes of variation (extrinsic to the process) represented by the overall performance should be eliminated, and the process should be continuously monitored to minimise the natural causes of variation (15.99%), thus improving Cpm. Otherwise, the process will be considered not capable (Fig. 9).

The mean was closer to USL, as indicated by the overall (PPL) and potential (CPL) process performance, based on which Cpk and Ppk were calculated, respectively. The fact that Cp and Pp were under 1.33 may result from the fact that 20% of observations were below the LSL (observed performance). This indicates that variation outside LSL is due to low Cpk (0.33) and Ppk (0.30) compared with Cp (1.27) and Pp (1.15), respectively. It is worth noting that the Cpk was lower than Cp, indicating a smaller process variation than the interval between specification limits. However, the distribution cannot be considered to be centred on the target. The process capability for seedling consumption (Mg ha^{-1}) for the day shift was found to be not capable both in the short and the long terms because Cp (0.40), Pp (0.34), Cpk (0.07), Ppk (0.06), and Cpm (0.26) were distant from each other. Also those indices were lower than the minimum acceptable value established for the present study (1.33). This result also indicates decentring of the process relative to the established target (Fig. 10), with the overall mean being closer to USL. The total value of the overall performance indicates that the process produced 46.22% of non-conforming observations for both the long and short terms (potential performance). Taking the specified target (19 Mg ha^{-1}) as the basis for calculation, this result shows that approximately 8.78 Mg ha^{-1} of sugarcane seedlings were outside the minimum required specifications (USL and LSL), as 43.21% of this value was above USL. This represents an excessive consumption of seedlings relative to the quality pattern or tolerance limit demanded by the producing unit. In this situation, it is not recommendable to eliminate the special causes of variation associated with the process but to adapt the process as a whole, redefining the levels, targets, staff training, and quality patterns, and subsequently monitoring the process frequently, so it becomes capable.

Night shift

The results obtained for the number of billets m^{-1} for the night shift were similar to the results obtained for the day shift. Therefore, The process was considered not capable to meet the specification limits, both in the long (Pp: 0.24) and short (Cp: 0.28) terms, regardless of the closeness of Cpm. This was mainly due to the process decentring as indicated by the distance of these indices relative to the lower value of Cpk (Fig. 11). Regarding the observed performance, the process produced 50% of items outside the specification limits, with an overall performance prediction of 56.03%. Therefore, if we eliminate the uncommon sources of variation from the process, the percentage of items outside the specifications is not greatly decreased (52.74%). Regarding the total number of shoots m^{-1} (Fig. 12), the process capability index (Cp) was slightly higher than Cpk. The process can be considered centred on the desired target due to the closeness of these values to Cpm (0.38). However, these indices were still lower than 1.33, which indicates that the process was not capable of producing satisfactory results according to the desired specifications. The process performance, considering only random causes of variation, exhibited 20.59% (10.83% below LSL and 9.76% above USL) of observations outside the specification limits. Therefore, the decision making for the diagnosis and elimination of special causes of variation, which are responsible for 25.00% of items outside the specification limits, should be thorough and may not be economically feasible for this variable during the operation. The number of viable shoots m^{-1}, regardless of the observed proximity between the potential and overall distribution curves, still exhibited a slight decentring relative to the target, which was also indicated by the proximity of Cp (0.14), Pp (0.14), and Cpm (0.10) (Fig. 13).

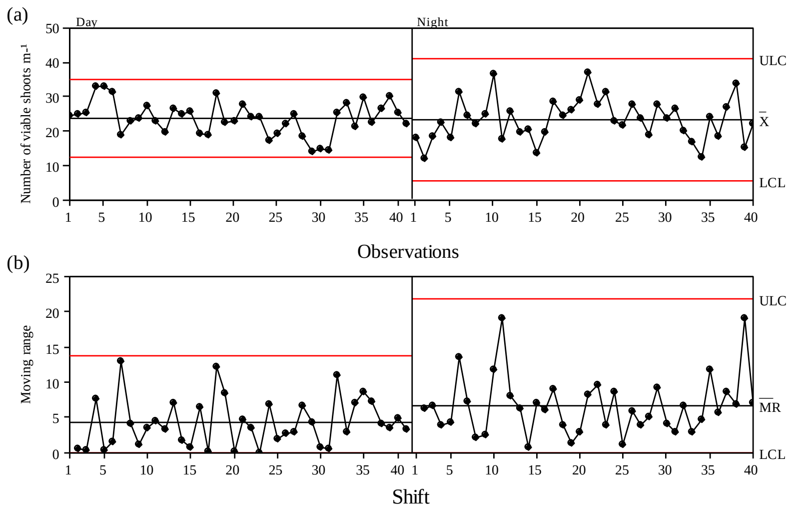

Fig 3. Control charts for mean number of viable shoots in mechanised sugarcane planting. (a) Individuals control chart. (b) Moving range control chart. UCL: Upper control limit. LCL: Lower control limit. $\bar{X}$: Individuals average. $\overline{MR}$: Moving range average.

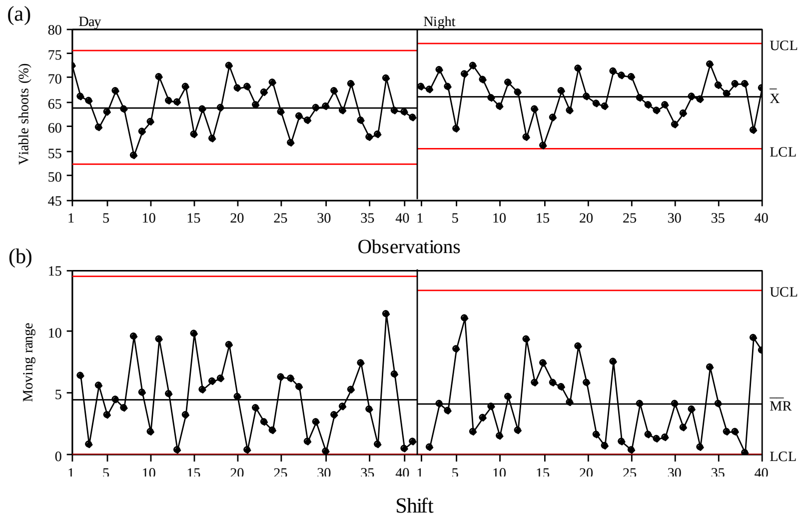

Fig 4. Control charts for mean % viable shoots in mechanised sugarcane planting. (a) Individuals control chart. (b) Moving range control chart. UCL: Upper control limit. LCL: Lower control limit. $\bar{X}$: Individuals average. $\overline{MR}$: Moving range average.

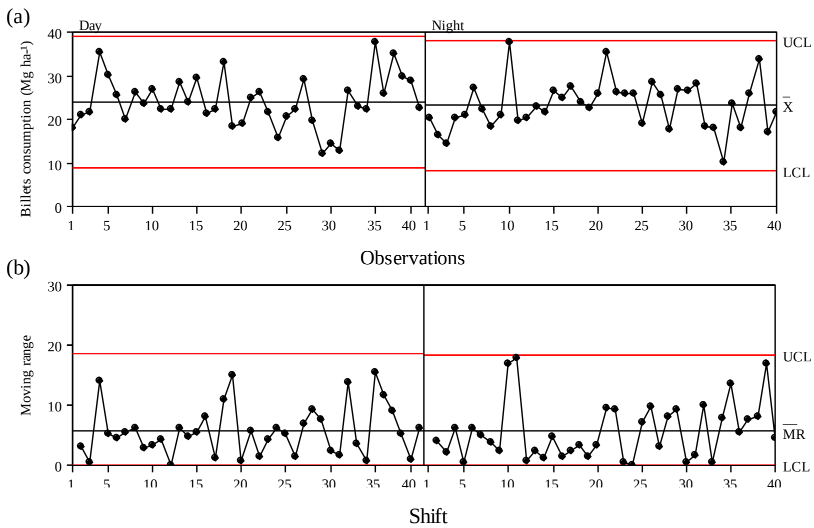

Fig 5. Control charts for mean seedling consumption in mechanised sugarcane planting. (a) Individuals control chart. (b) Moving range control chart. UCL: Upper control limit. LCL: Lower control limit. $\bar{X}$: Individuals average. $\overline{MR}$: Moving range average.

This result indicates that the process was not capable in the short and long terms because the Cp and Pp indices were lower than 1.33 for the potential and overall capability, respectively. The low values of Cpk and Ppk may indicate that the process was centred. However, there was variability outside the interval between the specification limits (negative Cpk and Ppk, indicating a mean value higher than USL, for the minimum process capability and process performance indices, respectively). This issue was also indicated by the higher values of the overall process performance, for which 70.40% of the observations were influenced by special and random causes of variation. This result indicates that if these values have even normal distributions and the process is stable, there will be strong variation among sampled values. This means that it is impossible to reach the full process capability unless measures for screening, continuous monitoring, and operation improvement as a whole are employed. The analysis of the overall and potential distribution curves indicates that the process was not centred on the target (Cp>Cpk and Pp>Ppk, respectively). However, Cp and Pp were high and may exhibit lower variation within the specification limits (distribution more centred on LSL than on the target). The association of these two factors indicates that the process was not capable of meeting the expected results within the specification limits in the long term ($Pp < 1.33$) but that the expected results might be met in the short term ($Cp > 1.33$) for the percentage of viable shoots during the night-time operation shift (Fig. 14). The analysis of the potential performance of the process indicates that if the special causes of variation are eliminated, namely the 6 M factors of production (Machine, Method, Materials, Measurement, Man, and Mother Nature), there will be only 4.57% random causes left acting on the process. In this situation, a higher frequency of process monitoring can be recommended to eliminate those variations, thus improving the potential and overall process capability. The seedling consumption (Mg ha^{-1}) during the night shift was similar to the seedling consumption of the day shift. The process was also considered not capable of producing satisfactory results in the short and long terms (Cp and Pp, respectively), as indicated by the potential capability (Cp, Cpk, and Cpm lower than 1.33 and distant from one another) and overall capability (Pp, Ppk and Cpm lower than 1.33 and distant from one another) indices and by its decentring (Fig. 15). This indicates high variability resulting in item production outside the specification limits. The observed process performance showed that 55.00% of the observations were distributed within the specification limits. However, due to the controllable and uncontrollable sources of variation, the process was displaced towards USL (observed, overall and potential process performance). Most of the observations were distributed close to USL (CPU and PPU close to zero, resulting in lower Cpk and Ppk, respectively). In this situation, similar to the day shift, the re-adaptation and revision of the whole process also becomes necessary to improve this quality indicator because, although the control charts indicate the stability of the process, the high variability intrinsic to the process (potential performance = 39.60%) makes it difficult for targets to be met by focusing only on the process monitoring and on decreasing variability.

Discussion

Normality test and descriptive statistics parameters

The analysis of datasets, especially variability, can be used to monitor data dispersion over time and detect possible flaws occurring during the operation (Mudholkar and Natarajan, 2002; Kim and White, 2004). The study of descriptive statistics is also essential for assessing the general behaviour of datasets (Léon et al., 2005). Further information on the behaviour of datasets and their interpretation and on the analysis of normal distributions was explained by Bai (2003). Bai and Ng (2005) reported an association between the mean and standard deviation that can be used to predict data behaviour, with data monitoring over time, in which they somewhat affect the higher or lower variation of the dataset. A normal distribution of the data is a pre-requisite of statistical process control and the calculation of process capability indices to more accurately estimate process capability over time (Montgomery, 2004). Bakir (2012) reported that a normal distribution is desirable for performing process capability analysis and for such analysis to be representative. Further information on studies of normality associated with the use of statistical process control can be found in Chakraborti (2006) and Zhou and Tsung (2010).

Individuals and moving range control charts

A normal distribution is essential for determining the process capability of production, conforming items. Otherwise, the process can be underestimated and will not reflect the situation accurately, requiring data transformation to perform the analysis (Gonçalez and Werner, 2009). Further information on the effects of non-normality and process stability on the subsequent analysis of process capability can be found in Somerville and Montgomery (1996) and Abbasi (2009). Toledo (2008) studied the quality of mechanised planting operation in the region of Jaboticabal, São Paulo, Brazil using control charts and found some of them to be stable or to indicate a predictable process suitable for the analysis of process capability, similar to this study, for which the process capability could be estimated. According to Shinde and Katikar (2012), the use of statistical process control for the monitoring and consequent development of improvement plans to increase the quality of produced items is essential for reducing production costs by decreasing the production of defective items. In this study, all evaluated quality indicators were found to be related to the production costs of mechanised sugarcane planting, and if this operation is well controlled and monitored over time, its financial returns can be increased.

Analysis of process capability for day and night shifts

The analysis of process capability or capacity is essential to obtain more accurate results for certain agricultural operations in the short and long terms. This analysis makes it possible to determine whether the operation is feasible over time while meeting the established targets, an assessment that is not as accurately performed using individuals control charts. The use of this tool to estimate process capability has only recently been applied to the agricultural mechanisation of sugarcane crops (Peloia et al., 2010), and similar studies are scarce. Mechanised sugarcane planting in India was found to be an excellent alternative to decrease manpower in production units (Singh et al., 2011). Moreover, this system requires that the sugarcane billets be chopped prior to planting, with a pre-set size and potential number of shoots per billet to improve the quality of sprouting and subsequent crop tillering, regardless of the operation shift. Kumar and Singh (2012) studied mechanised sugarcane planting in India using a sugarcane planter Khalsa P-603 model of lower weight (different than the one used in this study) with a 0.75 m planting distance. They reported that the length of the billets varied between 330 and 335 mm, depending on the cultivation region, with approximately 8 to 12 billets per m^{-1} furrow.

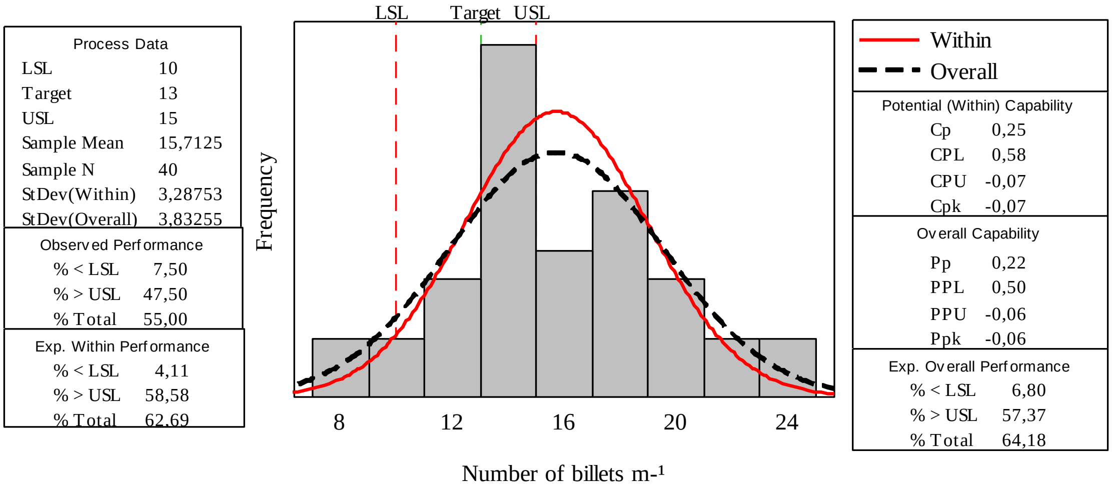

Fig 6. Analysis of process capability for number of billets m^{-1} for the day shift in mechanised sugarcane planting.

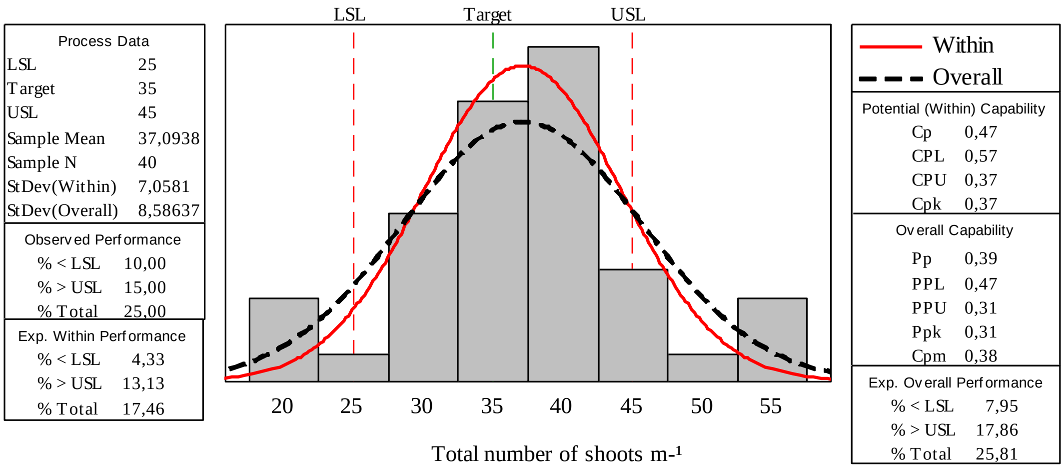

Fig 7. Analysis of process capability for total number of shoots m^{-1} for the day shift in mechanised sugarcane planting.

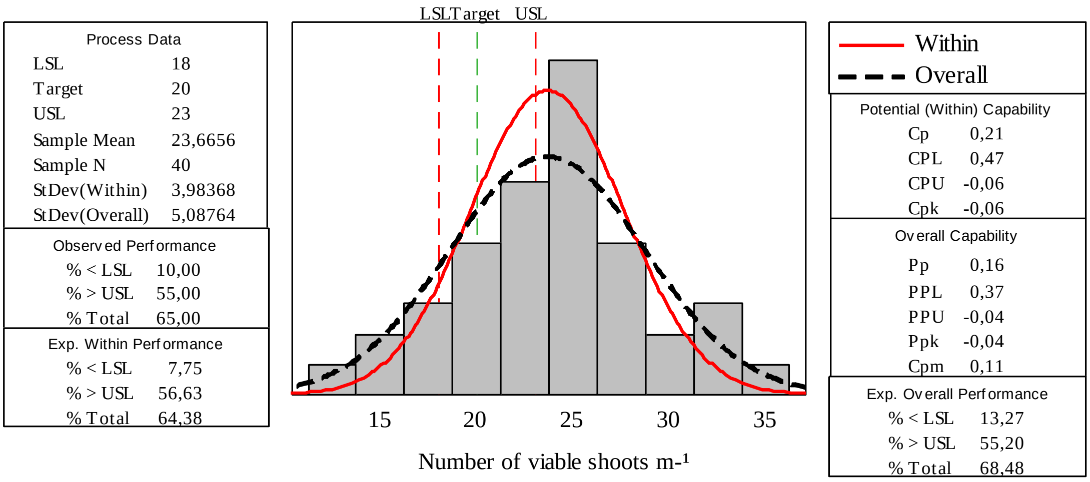

Fig 8. Analysis of process capability for number of viable shoots m^{-1} for the day shift in mechanised sugarcane planting.

This result contrasts with the values of the present study, with an average of 14 to 15 billets m^{-1}. However, the authors did not use statistical process control analysis methods. Noronha (2012) studied mechanised sugarcane planting in the MEIOSE system in the state of São Paulo, Brazil, using statistical process control and individuals and moving range control charts to monitor the operation, and reported approximately a 50% lower average number of billets than the results in the present study. This result contrasts with the present study and may be detrimental to the initial crop tillering due to the potential damage to the shoots.

Silva et al. (2011) studied the technological pattern of precision agriculture in the state of São Paulo and observed that the use of sensors is rare in sugarcane production and would possibly improve productivity, decrease production costs, and improve the quality of operations. This, together with the present study, clearly indicates that the presence of a sensor capable of quantifying the distribution of billets in mechanised planting, according to the adjustment of the rotation of the conveyor belt. It would be a valuable solution for decreasing the distribution variability over the working hours, regardless of the operation shift, which would potentially decrease external sources of errors caused by the tiredness of workers over time. According to Rípoli et al. (2007), who studied the quality of sugarcane planting with seedlings originating from mechanised harvest, the number of total shoots m^{-1} can be decreased by allocating a high number of shoots to the planting furrows, with no significant effects on productivity. This case may hold for the present study if the continuous monitoring of planting is not performed carefully, as some values were above the USL. Czarski and Matusiewicz (2012), used the statistical process control associated with a measurement system analysis. They found that the process was not capable of producing satisfactory items, independently of the process centring on the target. The same authors reported that due to high Cp and Cpk (1.17 and 1.14, respectively); adjustment measurements should be performed for the process to become capable, which contrasts with the present study. Such comparison between Cp and Cpk and between Pp and Ppk is essential because Cpk and Ppk alone cannot accurately represent process centring. When the standard deviation is very small, Cpk and Ppk are high because they are inversely proportional. These values alone give no information on the average between specification limits (Montgomery, 2009b). Zhang et al. (2009) performed tests using the modelling of sugarcane row crop dividers for mechanised harvest. They reported that the tilting of the stalks to be lifted and should not be below 15º. So, there is no damage to the stalks and consequently the shoots; thus, leading to decreased shoot viability, being lifted and directed to the cutting mechanism, which could influence the initial development of the crop. This was also confirmed in the present study. However, it should be highlighted that the flow of crop material from the field, due to uncontrollable factors, sometimes makes these ideals hard to achieve. This subject was also discussed in detail by other authors (Song et al., 2010; Xie et al., 2011). Hosseinifard et al. (2009) observed that the higher the proximity between the estimated and real averages (higher accuracy), the lower the process variability, as indicated by the standard deviation (higher precision). This relationship is an important way to estimate the real process capability. For this study, if the estimated target was close to the overall average (real), the process would have higher potential to maintain its capability. Toledo (2008) analysed the capability of peanut sowing operations and reported a similar results to this study. The author reported that 100% of the observations were above the USL, preventing the process from becoming capable in the long term. The observed process capability indices for the percentage of viable shoots m^{-1} may be somewhat similar to the ones reported by Garza-Reyes et al. (2010). The authors performed a general analysis of measures of certain equipment in the production line based on the process capability index and developed a Cp/Cpk ratio index, for which they determined a minimum value for the process to meet the specification limits, with the full capability of meeting this value both in the short and long terms. These authors reported, the higher the Cp/Cpk ratio, the better the process performance. This case may be relevant to the present study because the creation of such an index could substantially improve the process quality through rigorous quality control with the goal of reaching the established target. The process capability analysis of losses has been reported to exhibit capability indices below the minimum required value (1.33), resulting from mechanised sugarcane harvest, according to types of soil preparation (Reis, 2009). This result shows that the process is not capable of meeting the specifications, in both the short and long terms. In contrast, the operation evaluated in this study has the potential to meet the specification limits in the short term, and if improvements are performed to further decrease extrinsic sources of variation, then it may also be able meet long-term demands, which is essential for the management of this activity. The process capability indices found for seedling consumption (Mg ha^{-1}) can be related to the values reported by González and Sánchez (2009), who studied process capability using either univariate (similar to this study) or multivariate analysis. The authors reported that when multivariate methods of process capability analysis are used, an index can be created for the study of each factor independently of the process variation, with the goal of identifying the most critical parts of the process. Saghaei et al. (2009) used process control techniques, relating them to process capability, and specifically used CUSUM (phase II - multivariate) control charts to monitor small variations of the process. They reported that the results satisfy the analysis for the production of conforming items. However, further studies would be necessary to establish the sample size and the remaining statistical bases. Following the same reasoning, Chen and Chen (2008) used fuzzy logic to infer multivariate methods for the analysis of process capability for the colours of STN displays and obtained satisfactory results, concluding that the use of multivariate methods is viable for the large-scale production of satisfactory items. Furthermore, Hosseinifard and Abbasi (2012) estimated the process capability for the monitoring of several profiles of production items using linear estimation methods (phase I - univariate) and reported good performance of the capability indices using the estimated dataset standard deviation as the basis of variation. Qiu et al. (2010) used modelling techniques to estimate the characteristics of nonparametric profiles, based on the analysis of the process capability, and reported that they can meet the required limits when properly analysed.

Materials and Methods

Plant materials and experimental conditions

The experiment was conducted in the Monte Alto municipality, state of São Paulo (SP), Brazil (21º16'42" S latitude, 48º24'21" W longitude), with an average altitude of 620 m, 6% average slope, and Aw climate according to the Köppen climate classification. The georeferencing of the area was performed using a GNSS receiver Trimble R6 (centi-millimetric positional accuracy), and the coordinates were recorded in the UTM (Universal Transverse Mercator) coordinate system.

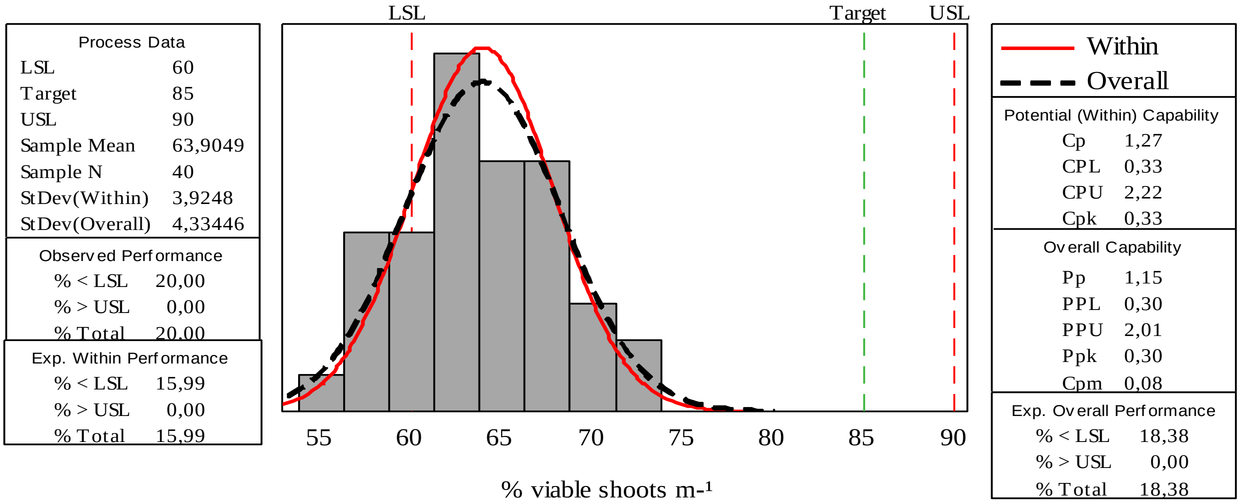

Fig 9. Analysis of process capability for percentage of viable shoots m $^{-1}$ for the day shift in mechanised sugarcane planting.

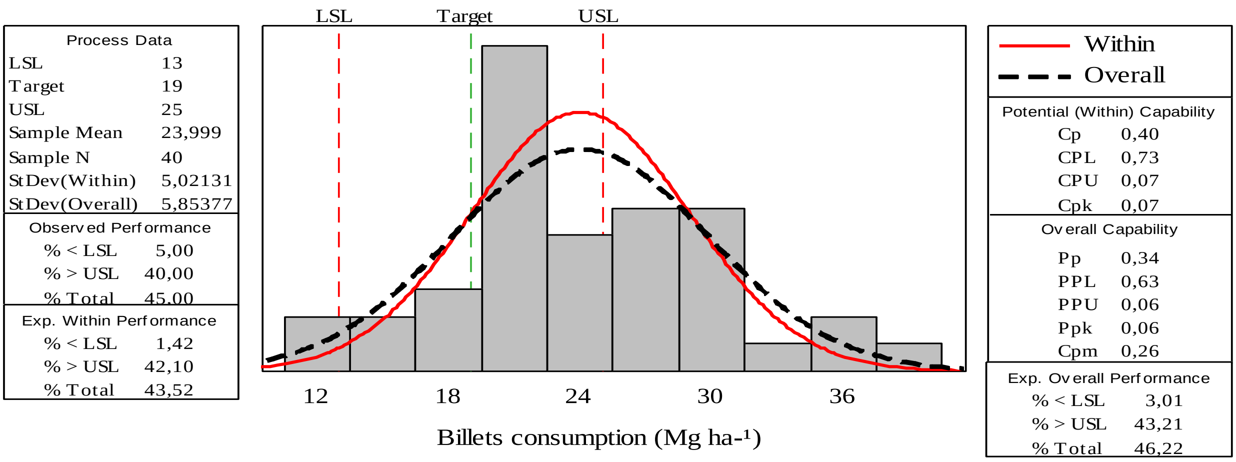

Fig 10. Analysis of process capability for seedling consumption Mg ha $^{-1}$ for day shift in mechanised sugarcane planting.

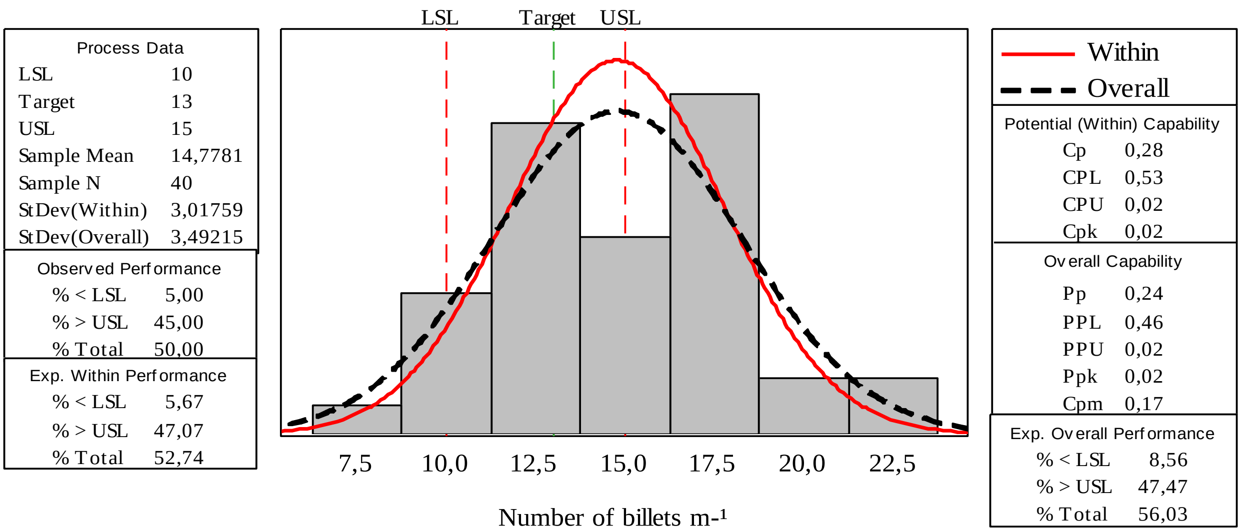

Fig 11. Analysis of process capability for number of billets m $^{-1}$ for night shift in mechanised sugarcane planting.

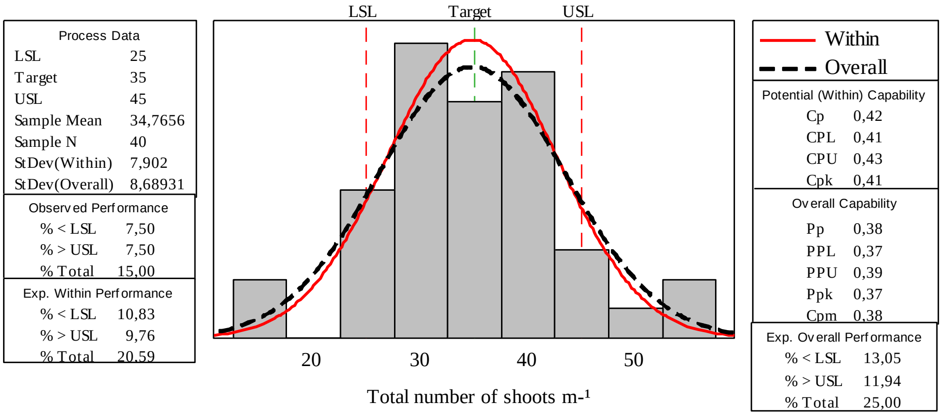

Fig 12. Analysis of the process capability for total number of shoots m^{-1} for the night shift in mechanised sugarcane planting

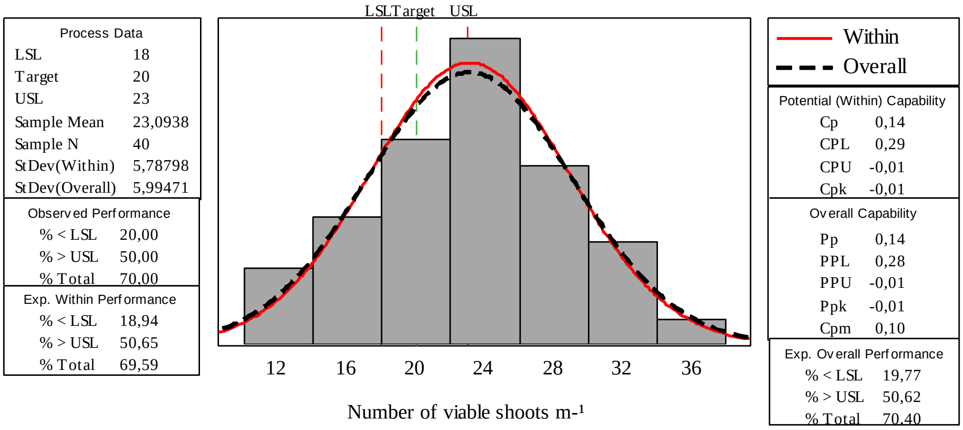

Fig 13. Analysis of process capability for number of viable shoots m^{-1} for night shift in mechanised sugarcane planting.

Experimental design

The experimental design was completely randomised, with the treatments being established during the evening operation period (15:00 to 23:00 PM) to allow the evaluation of the operation during both daytime (15:30 to 17:30 PM) and night-time (19:30 to 21:30 PM), without the need to change the operator; therefore, allowing better control of the experimental conditions. Two pre-defined sampling meshes were established, with 40 points (average of the left and right furrows), spaced 50 × 1.5 m from each other, with 40 points being evaluated during the daytime and 40 during the night-time.

Quality indicators or variables measured

The total number of billets was measured after mechanised planting (opening of furrows, seedling placement, and closing of furrows) by direct counting over four metres of the furrows evaluated, following the digging of the furrows using a hoe, carefully handled to avoid damage and/or injuries to the billets. For higher experimental control, the number of billets (units) for each replicate was counted by a single evaluator. The total number of shoots was measured by direct counting of the billets obtained previously in the four evaluated metres of the planting furrows (left and right), following the digging and removal of billets from the furrows using a hoe, carefully handled to avoid damage to the shoots. This counting was performed after the mechanised sugarcane planting (Voltarelli, 2013). The number of viable shoots was obtained by direct counting of the billets for total number of shoots in the four evaluated metres of the planting furrows, after the digging of the furrows (left and right) and subsequent removal of the billets using a hoe, carefully handled to avoid damage to the shoots. This counting was performed following the mechanised sugarcane planting (Robotham and Chappell, 2002). Viable shoots were defined as shoots that were not attacked by pests and diseases and were not damaged by potential fragmentations such as impacts during mechanised harvest, transport of seedlings to the planting area, unloading of seedlings inside the bucket of the planter, and subsequent distribution to the planting furrows. For greater experimental control, the number of total and viable shoots for each replicate was counted by a single evaluator.

The percentage of viable shoots was calculated using the following equation (Robotham and Chappell, 2002):

$$\% \, VS = \left(\frac{NVS}{NVS + NNS}\right) x \, 100 \tag{3}$$

Where,
% VS: Percentage of viable shoots;
NVS: Number of viable shoots m^{-1};
NNS: Number of non-viable shoots m^{-1};
100: Conversion factor.

Billets consumption was estimated (eq. 4) based on the values of biometric analysis of seedlings (billet mass), number of billets m^{-1} furrow, and spacing used for mechanised planting, for each planting furrow (left and right), and for the day and night operation shifts (Janine, 2007).

$$BC = \frac{m \ x \ Nr \ x \ Dp}{1000} \quad (4)$$

Where,
BC: Billets consumption (Mg ha^{-1});
m: Mass of billets in furrows (m kg $billet^{-1}$);
Nr: Number of billets (billets m^{-1});
Dp: Planting density (m ha^{-1});
1000: Conversion factor from kg ha^{-1} to Mg ha^{-1}.

Soil conditions

The studied area had been previously cultivated with soybean, and mechanised sugarcane planting was performed after its harvest. Periodic soil preparation (using both medium and levelling disc harrowing) was performed before soybean sowing, after sub-soiling at 0.50 m depth. The amount of straw left from the soybean crop was measured by sampling ten random points and was determined to be 938.03 kg ha^{-1} dry mass. Soil samplings were performed (0-0.20 m) to determine soil texture. The soil was found to consist of 78% sand, 6% silt, and 16% clay, classified as exhibiting medium texture. The soil mechanical resistance to penetration and soil water content were determined according to Asabe (2006) and Buol et al. (2011), respectively. Eighty sampling points were sampled for soil resistance, 40 points for each operation shift, and 160 samples were collected for soil water content, 80 for each operation shift, from layers of 0-0.15 and 0.15 - 0.30 m. The layer presenting the highest resistance to soil penetration was from 0.10 to 0.20 m depth (3.14 MPa). The soil water content was 7.0% (daytime) and 8.5% (night-time) at 0-0.15 m depth and was 6.5 (daytime) and 9.0% (night-time) at 0.15 – 0.30 m depth.

Tractor and planter characteristics

Mechanised sugarcane planting was performed on 27/03/2012 using a tractor-planter set composed of a 4 × 2 FWA tractor, with engine power of 134.0 kW at 2200 rpm, 6 cylinders, with a 17:1 compression ratio, 600/65R28 front wheeling and 710/70R38 back wheeling, both R1W, and a 2-row chopped sugarcane planter, with capacity for six tons of seedlings for planting, a fertiliser box of 1.300 kg, 3.60 metres wide, with 600/50 22.5 wheeling, with shanks spaced by 1.50 m.

The tractor was operated with gauge adjusted to 2.70 m and in work gear 1B. The sugarcane cultivar planted was RB83 – 5054, which is suitable for mechanised harvest and appropriate for medium fertility soils. During the planting operation, 400 kg ha^{-1} fertiliser and 100 L ha^{-1} imidacloprid insecticide spray were applied. The set was equipped with an automatic steering hydraulic system for planting alignment (automatic pilot), consisting of an on-board computer Fmx®, GPS receiver AgGPS (both Trimble), and other accessories. This system uses the Real Time Kinematic (RTK) positioning method, with rover-based communication via radio signal, reaching approximately 0.025 m horizontal positioning quality.

Statistical analysis

The normality of the data was verified by the Anderson-Darling test, a measure of the closeness of the points and the line estimated in the probability, giving greater stiffness to the analysis (Acock, 2008).

Statistical process control I-MR control charts (individuals and moving range) were used to assess the process stability. These charts display central lines (overall average and mean amplitude), an upper line for the upper control limit (UCL), and a lower line for the lower control limit (LCL), calculated based on the standard deviation of the variables (for UCL, average plus three times the standard deviation, and for LCL, average minus three times the standard deviation, when greater than zero). The charts were used to identify non-randomness caused by external factors and to evaluate the quality of the operation, using the previously described variables as quality indicators (Montgomery, 2009a).

Montgomery (2009a) reported that process statistical control charts can be interpreted by considering a process 'in statistical control' or 'out of statistical control'. These terms can be defined as follows: a process in statistical control is predictable, significant, or stable: only variability intrinsic to the process takes place, i.e., variability that results from random causes of variation, both for individuals and moving range control charts. A process out of statistical control is unstable: special causes of variation are in play, resulting in the instability of the process as its behaviour becomes unpredictable relative to the expected pattern.

To detect the presence of special causes of variation in control charts, i.e., resulting from variability extrinsic to the process, the following recommendations by Western Electric Company (1956) and Montgomery (2009) were used:

Test 1: One or more points outside the upper and lower control limits;

Test 2: Alternation of 14 points above and below the central line;

Test 3: Sequence of 10 points on either side of the central line;

Test 4: Seven consecutive points in a decreasing or increasing sequence.

Individuals control charts should be implemented to monitor variables that influence items or process quality over time (Minitab, 2007). A given variable can be monitored by successive samples, which can be collected at certain time periods, from production lots, in real time, or from raw material lots, amongst other possibilities; i.e., the variables possess measurable characteristics of a given process and can be considered continuous (Werkema, 2006).

Moving range control charts were used to detect variability throughout the process resulting from the individuals control chart, for which values consist of the absolute value of the difference between two consecutive points. When the difference between the two points exceeds the control limits, then special causes of variation are potentially influencing the process quality (Montgomery, 2009a), reflecting the variation within the sample at a given time-point. The joint use of the moving range and individuals charts is essential for the monitoring and understanding of possible special causes affecting the process and thus for trying to minimise its variation, which will increase its quality (Minitab, 2007).

The analysis of the process capacity or capability was developed to predict how many of the items produced during the production process will meet the specifications defined by the upper and lower control limits. Such limits are determined by managers to achieve the desired quality target of a given process. Thus, this analysis allows the relation of the variability intrinsic to the process to its specifications (Voltarelli, 2013).

To perform the process capability analysis and evaluate whether the process can produce conforming items over time, both in the short and long terms, the following assumptions must be met (Montgomery, 2009b):

Assumption 1: The data set should display a normal distribution; Assumption 2: The individuals and moving range control charts should exhibit only common or natural causes of variation, and all points should be within the control limits.

This analysis is represented by a histogram used to assess the normality of the data and by several capability indices used to calculate the number of defects or products outside the specification limits that may be produced by the process, with and without the removal of extrinsic causes of variation when present (Montgomery, 2009b). The specification limits (upper and lower control limits) and the target to be met are represented by vertical lines on the capability histogram. Comparing the histogram with these lines enables determination of the number of observations close to the target, their frequency, and the observations within the specification limits. For this study, the minimum acceptable level of process capability to meet the specification limits, in the short and long terms, was calculated to be 1.33. The calculation of the capability indices and the remaining analysis of process capability were performed based on the methodology described by Montgomery (2009b).

Specification limits, also called engineering tolerances, are parameters based on technical recommendations and agricultural criteria, which can establish better quality and economic standards for the process. They can be based on the literature or on typical values for the evaluated quality indicators (Table 2).

The control specification limits were defined in association with the managers of the operation (supervisor and agricultural manager) and with the other workers (tractor operator, planter cabin operator, and evaluators of post-planting quality for each operation shift), through brainstorming. The goal was to achieve a 90% final operation quality, according to the perspective of this production unit, to evaluate the capability of sugarcane mechanised planting for the day and night shifts.

A unit value was set for all evaluated quality indicators, which was also considered the individual value for the analysis of process capability, by adding the values obtained for the left and right furrows. Therefore, an average sample value was used based on a total of 40 points and/or replicates for each operation shift evaluated.

This decision was made because both furrows must display quality for the successful process, considering a single planting furrow, left or right, as capable had no practical relevance for this planting system and operation. For the process to be considered capable, it should be continuously monitored, improved, and optimised. Therefore, it becomes difficult to maintain a stable process by evaluating factors individually, due to the high variability and dynamism throughout the operation.

Conclusions

The quality of the mechanised sugarcane planting operation varied according to the operation shift, being higher for the night shift. The evaluated quality indicators of mechanised sugarcane planting were not considered capable of reaching the set targets (Cp and Pp < 1.33), independently of the process stability, except for the percentage of viable shoots for the night shift. The development of an improvement plan and the setting of new targets are essential for the mechanised sugarcane planting operation, where the goal is to increase the quality of operations and produce items within specification limits over time.

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