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Monitoring performance indicators of mechanized agricultural operations through a systemic method

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ABSTRACT: Key performance indicators (KPI) are essential to decision-making in an organization, but the approach to analysis and composition used in the formulation of the KPIs can lead to errors. Analysis based only on averages does not allow for discriminating between variations that are natural to the process or special cases which require investigation. The use of control charts can identify this differentiation. However, when several charts are presented encompassing different measurement units and scales, systemic interpretation can be impaired. To assist in this interpretation, this research study aimed at proposing a method to facilitate the analysis of control charts when multiple indicators are employed in the monitoring of agricultural operations. Based on the data obtained over 26 weeks from a mechanized sugarcane (*Saccharum officinarum* L.) harvesting front, six indicators were defined and analyzed through individual control charts and, systemically, through a standardized group control chart. Results show that the points identified as being outside the control zone (special causes of variation) according to the standardized group control chart were the same as those identified by the six individual charts, which demonstrates the potential of this method to summarize the information with no loss of quality of analysis.

Keywords: KPI, management, control chart, agricultural mechanization, sugarcane harvest

Introduction

An approach to management based on the analysis of key performance indicators (KPIs) supports the decision making of an organization. A systemic method of analysis consists of monitoring simultaneously KPIs linked to the different aspects interconnected in a complex process to provide a holistic view and prioritize the balance between them (Jones and Kijima, 2018). Despite the importance of using KPIs systemically, lack of familiarity with and training in analytical methods is still pervasive, giving rise to interpretations that may lead to errors (Hermans et al., 2018). A common approach to analysis is to compare KPI with a predefined target. Whether the target is reached or not, corrective actions should be applied, and if the resulting performance is considered satisfactory no further action is required (Bergman and Klefsjö, 2010). This approach to analysis may lead to erroneous conclusions (Caulcutt, 1996). When natural variations inherent in the process are not separated from special ones, the search may focus on problems that do not exist. To distinguish the natural from the special, control and process capability charts that allow for differentiating company specifications and statistical control limits can be used (Dull and Tegarden, 2004; Montgomery, 2019; Roth, 2005).

The use of control charts, mainly "individual value and moving range", "mean and range" and "exponentially weighted moving average", is increasing in frequency in the monitoring of agricultural operations such as damage to shoots and its distribution in the furrow for planting and an index of damage and disturbance in ratoons, cutting height, total visible losses and length of billets for the harvesting of sugarcane, *Saccharum officinarum* L. (Cortez et al., 2016; Paixão et al., 2021; Peloia et al., 2010; Toledo et al., 2013; Voltarelli et al., 2014; Voltarelli et al., 2015), cutting height and losses for soybean harvest, *Glycine max* L. (Menezes et al., 2018), distribution of seedlings, plant population and yield for sowing of corn, *Zea Mays* L. (Ormond et al., 2019).

Using separate control and capability charts for different KPIs may hinder the analysis and interpretation of results systemically when different units and scales are involved, resulting in a prohibitively large number of control charts (Boyd, 1950; Montgomery, 2019). Thus, the potential of KPI may not be fully exploited in a systemic method that supports decision making. To minimize these difficulties of analysis, the aim of this study was to suggest a method to facilitate analyses of control and capability charts where there are multiple indicators for agricultural operations.

Materials and Methods

The data utilized herein refer to a mechanized harvest front that operated on green sugarcane, with a 1.5 m row, under normal working conditions for 26 weeks, from Apr to Oct. In addition to the harvester, the front was composed of three haulouts that receive the cane billets from the harvester and load the trailers that transport them to the mill. The sugarcane mill, located in the northwest region of the state of São Paulo, Brazil (20°43′44″ S, 50°57′32″ W, altitude of 359 m), had a processing capacity of four million tons of cane per year.

The data were registered by the harvester operators' and mill's support team on check sheets and then structured to produce the following six weekly performance indicators: (1) operational processing capacity (OPC), expressed in mass of harvested cane per worked time period (t h^{-1}); (2) managerial efficiency (ME) in percentage (%) corresponding to the ratio between worked time and total time of climatic aptitude; (3) fuel consumption (FC), in volume of fuel consumed by the harvested mass of cane (L t^{-1}); (4) total visible losses (TVL), given in mass per area (t ha^{-1}), collected according to Ripoli and Ripoli (2009); (5) mineral impurities (MI), in mass of impurities per mass of harvested cane (kg t^{-1}) and (6) vegetal impurities (VI), the ratio between vegetal impurity mass and unit of cane mass (t), in percentage (%). The specification limits, considered as targets, adopted for each one of the indicators were: (1) OPC: 48.0 t h^{-1}; (2) ME: 65 %; (3) FC: 0.82 L t^{-1}; (4) TVL: 3.4 t ha^{-1}; (5) MI: 12.0 kg t^{-1}; and (6) VI: 6 %.

These six indicators, according to the mill's technical board cover the three main aspects of the harvesting process that should be tracked and analyzed together frequently: cost (FC and TVL); quality (MI and VI) and delivery (OPC and ME).

The hours of the harvester worked correspond to the sum of times of harvesting (machine executing the function for which it has been designed), unload, shunting, and unblocking. The inactive times, downtime hours, have been classified as: (1) climatic inaptitude, corresponding to the precipitation period or excessive soil humidity; (2) corrective maintenance, unplanned stop due to failure or breakage; (3) preventative maintenance, planned stop for maintenance that also includes filling, washing and lubrication; (4) transport unavailability: absence of forwarder due to lack of synchronism between harvester, forwarders, and trailer.

No changes were made to the method and frequency with which these indicators were collected and made available (weekly). This research study is restricted to the visualization and interpretation of data collected in the field that originated the performance indicators. The method and frequency of collection followed the procedures determined by the mill for operators and teams.

One control chart for each performance indicator has been constructed using individual values and median moving range (x and $\tilde{R}m$). The option for individual values is related to the fact that the number of samples collected in each time interval is equal to one week. Calculated as the difference in modulus of two consecutive values, the median moving range was used rather than the mean due to its lower sensitivity to discrepant values (Bryce et al., 1997; Clifford, 1959). This chart has not been plotted because its analysis does not provide any useful information on the process variability (Rigdon et al., 1994).

The control chart is composed of individual values of indicator (Y-axis) by sampling time (X-axis) week. Its interpretation is based on the function of upper control limit (UCL) and lower control limit (LCL), represented by lines parallel to the X-axis. The control limits lie three standard deviations ($\hat{\sigma}$) from the average of individual values ($\bar{x}$). When a point is beyond these limits, the interpretation is that there was a special cause of variation which has to be investigated, looking for potential assignable causes. Other indicators of special causes of variation are the presence of runs (shift in KPI level), trends (points steadily decreasing or increasing), or cyclic patterns, In all other cases, the point's variation is considered normal and the behavior of the indicator is considered predictable. $\hat{\sigma}$ has been estimated (Eq. (1)) by the multiplication of the median moving range by a constant factor (Montgomery, 2019):

$$\hat{\sigma} = \tilde{R}m \times 1.047 \tag{1}$$

where: $\hat{\sigma}$ - estimated standard deviation; $\tilde{R}m$ – median moving range; 1.047 – factor, Montgomery (2019).

As it is a chart of individual values, a horizontal line representing the respective specification limit has been added.

For facilitating the visualization and analysis of multiple performance indicators, a standardized group control chart was developed. Standardized individual values were obtained according to Eq. (2), Z-score, and measured in units of standard deviation.

$$x_Z = (x - \bar{x}) / \hat{\sigma} \tag{2}$$

where: x_z - standardized individual value; x - individual value; $\bar{x}$ - average of individual values; $\hat{\sigma}$ - estimated standard deviation.

The following standardized markers, the upper control limit (ZUCL), lower control limit (ZLCL) and average ($\bar{x}_Z$) assumed, respectively, the values $+3.0$, -3.0 and 0.0, for all indicators. Based on the individual values, limits, and average, the group control chart, adapted from Boyd (1950), was constructed where only the highest and the lowest values in each week were plotted and identified by their respective KPI. If a KPI gave the highest or lowest value four or more consecutive times (Nelson and Stephenson, 1996), it constituted a shift in performance and was considered a point where a special cause of variation was present.

To compare the performance of each indicator to its respective specification limit, a box plot chart on a standardized scale for each indicator was constructed. The standardization of scale for indicators OPC and ME, which have lower specification limits, was calculated by Eq. (3). For indicators with upper specification limits, TVL, FC, MI, and VI, Eq. (4) were applied. Thus, the standardized upper specification limits (ZUSL) and standardized lower specification limits (ZLSL) and $\bar{x}_Z$ assumed the values of -1.0 $+1.0$ and 0.0, respectively.

$$ZLSL = (x - \bar{x}) / (\bar{x} - LSL) \tag{3}$$

$$ZUSL = (x - \bar{x}) / (USL - \bar{x}) \tag{4}$$

where: *ZLSL* - standardized lower specification limit; *ZUSL* - standardized upper specification limit; x - individual value; $\bar{x}$ - average of individual values; *LSL* - lower specification limit; *USL* - upper specification limit

The points suggesting the presence of special causes of variation in the six individual values charts were compared with the cases identified by the standardized group control chart, and the capability to meet the specifications through the individual values charts and the box plot on a standardized scale.

Results and Discussion

The harvester's accumulated inactive times per week are shown in Figure 1. The climatic inaptitude, which represents 12 % of total time or 42 % of downtime, stood out over the weeks and, from a management point of view, was not actionable and was poorly predictable. The second most important cause of downtime was preventative maintenance, with 7 % and 26 % of total time and inactive time, respectively.

Analysis of control charts showed that only the indicators FC, MI and ME presented special causes of variation during the period, Figures 2A, B, C, D, E and F. In the case of FC, there was a trend of decreasing values from week 19 to 24. For MI, the values observed in weeks two, six, seven, and eight were above the UCL and a shift in the KPI level, and consecutive values were below the average, during weeks 16 to 22. For the indicator ME, this occurred in week four and was related to LCL.

For indicator FC, the trend started in week 19 (0.65 L t^{-1}) and the values observed decreased up to week 24 (0.57 L t^{-1}). A hypothesis that may be tested to explain this behavior is whether the variability of sugarcane yield influenced fuel consumption during these weeks since it is known that the higher the yield, the lower the consumption in L t^{-1} (Ramos et al., 2016). Despite the fact that a lower FC is the desired performance, the investigation of this behavior is still recommended since it may be replicated for further performance improvement.

The indicator MI presented an average of 6.3 kg t^{-1} but during weeks two, six, seven, and eight it varied in the interval between 10.4 and 12.7 kg t^{-1}. On the other hand, during the period between weeks 16 to 22, the values observed were in the range of 2.6 to 4.4 kg t^{-1}. This fact can be attributed to the rainfall in the period (climatic inaptitude) since the soil particles adhere to the cane stalks on account of the humidity (Ripoli and Ripoli, 2009). The non-parametric coefficient of Spearman (ρ) between climatic inaptitude and MI, during the 26 weeks, was 0.67 ($p < 0.01$), which corroborates the statement. The correlation is valid for the whole period and not only for the weeks when special causes occurred. When the performance indicator is influenced by seasonal factors, in this case rainfall, it can be directly incorporated into the control chart model and then the variability due to seasonal factors is excluded (Mandel, 1969).

For ME, the indicator average during the period was 78 %, while in week four this value was 55 %. During this week, the summed time of harvester stopped due to the unavailability of transport corresponding to 61 % of total downtime, or 52.5 h. In the other weeks, downtime waiting for a haulout was always below 16.6 h and in 75 % of these weeks, the value was lower than 9.1 h.

Indicators OPC, TVL, and VI are within the control limits and are considered predictable and their

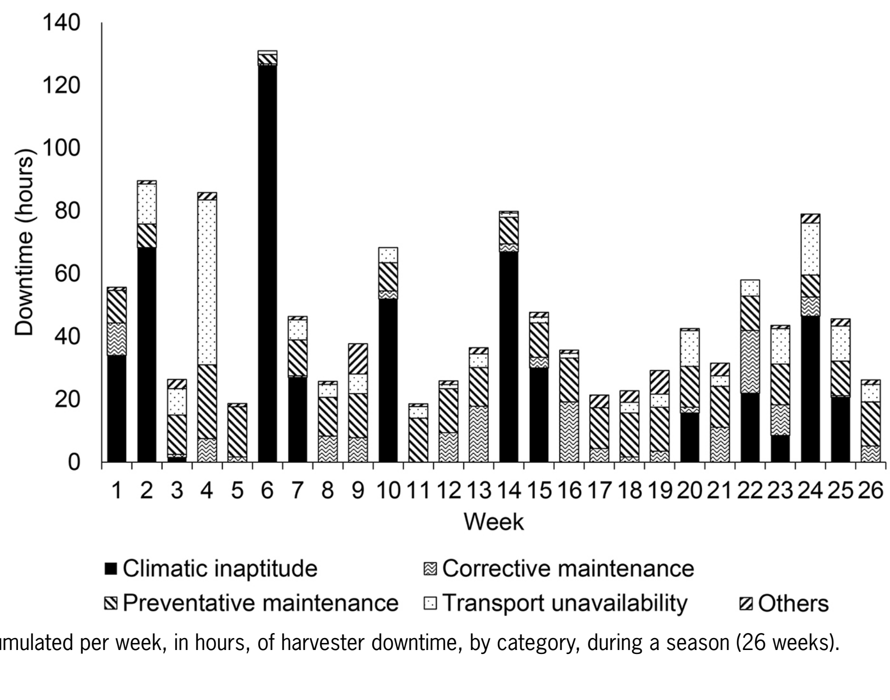

Figure 1 – Time accumulated per week, in hours, of harvester downtime, by category, during a season (26 weeks).

variations are attributed to causes inherent in the process. Being in statistical control does not imply that the process met the target, or that it cannot be improved. The comparison of specification limits with the control ones shown in Figure 2A, B, C, D, E and F gives rise to two scenarios.

The first scenario is when the specification limit is between the LCL and UCL as in the case of TVL, VI, and OPC. In these situations, it is expected that, in certain periods, the target will not be reached due to the natural variability of the indicator, and there is no room for investigating the special causes related to unsatisfactory performance. For TVL, for example, the specification limit is that losses have to be lower than 3.4 t ha^{-1} (the lower, the better). However, the UCL of the process is 5.0 t ha^{-1}, prompting the expectation of losses above the specification limit in approximately three out of every ten weeks. In this scenario, it is

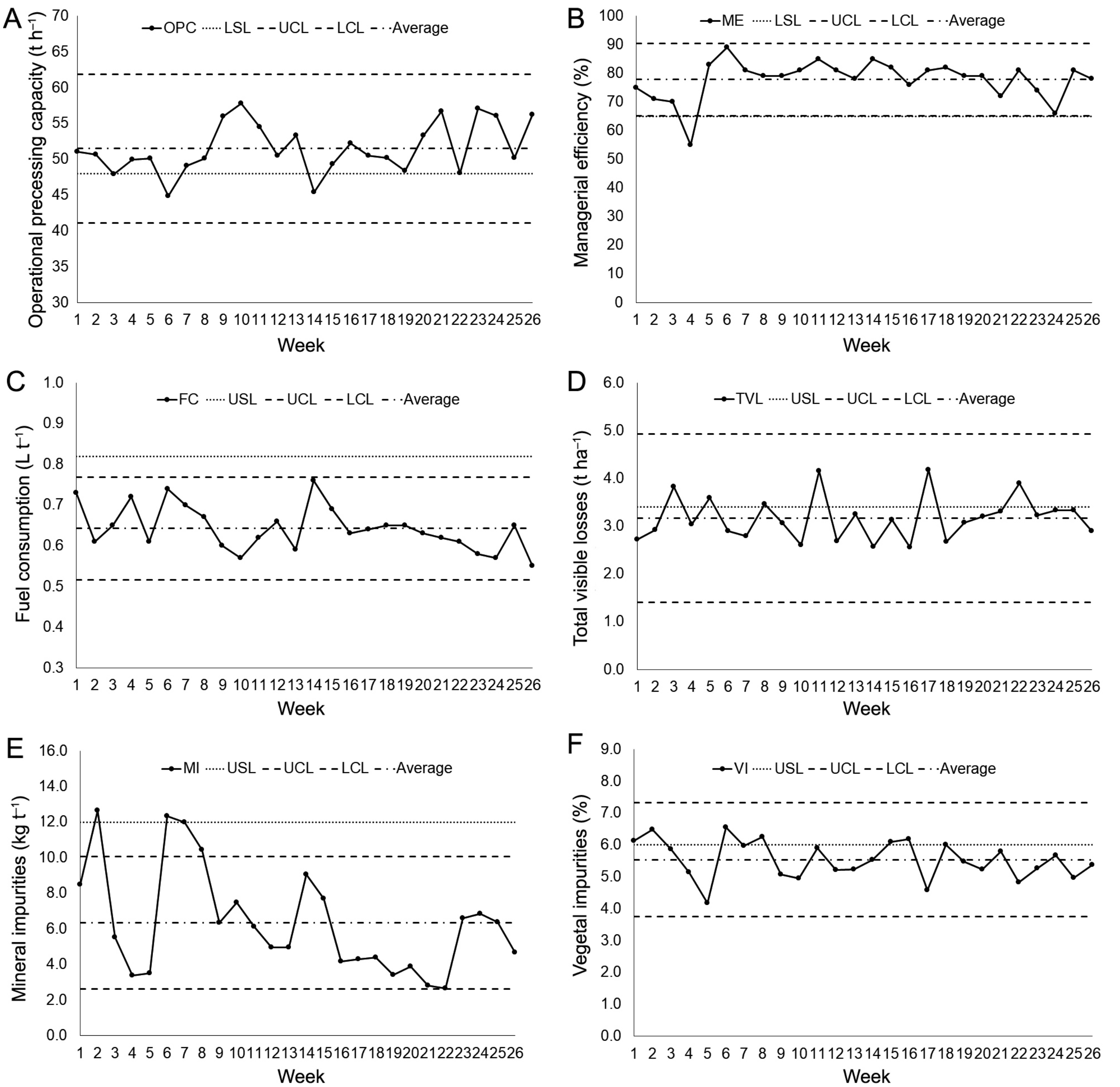

Figure 2 – Individual values control chart with standard deviation estimated by median moving range for performance indicators (A) Operational processing capacity (OPC), (B) Managerial efficiency (ME), (C) Fuel consumption (FC), (D) Total visible losses (TVL), (E) Mineral impurities (MI), and (F) Vegetal impurities (VI) referring to a sugarcane harvester operating during a season. USL = upper specification limit; LSL = lower specification limit; UCL = upper control limit; LCL = lower control limit.

necessary to reduce the natural variability and/or the average so that the values obtained are below the specification limit. A way to promote this reduction is to modify the process, a responsibility credited to the managerial level.

The second scenario corresponds to the specification limit outside the interval between LCL and UCL, cases referring to MI, FC, and ME. For indicator MI, the value of the specification limit is 12 kg t^{-1} (the lower, the better) and it is above the UCL. The process is meeting the specification, but there are special causes to be investigated. They are not considered as natural variability, do not belong to the process, and there is room for explanation, which can be provided by the harvest team itself, at the operational level. In certain cases, those having minor impact can be disregarded and do not trigger corrective actions, such as when the target is reached.

In the standardized group control chart for the six performance indicators, Figure 3A, special causes in weeks two, four, six, seven, eight, and from 16 to 22 were found. In the case of week four, the value of the performance indicator ME is below the ZLSL and in the others, they are associated with MI and above the ZUSL or there was a shift in the performance level (MI was the lowest observed value during seven consecutive weeks) due to rainfall as previously explained.

Due to their either exceeding the control limits or having a performance shift, points identified as outside the control zone in the standardized group control chart were the same ones found in the six individual charts. It was, however, not possible to identify the descending trend in FC, a known disadvantage of this type of control chart (Boyd, 1950; Montgomery, 2019). Thus, this example demonstrates the potential of this method for summarizing the information with a minimum loss of quality, and it could be extended, for example, to summarize the performance of multiple harvest fronts in one chart only.

A disadvantage of using a unique chart for multiple indicators is the impossibility of including the horizontal line with the respective specification limit, a fact that can be mitigated with process capability charts, and plot on a standardized scale, Figure 3B.

The analysis of standardized specification limits (Figure 3B) is based on a comparison of each box plot with the line delineating the limit. For performance indicators with ZLSL – OPC and ME – the more above the line the box plot, the more the indicator will be capable of meeting the specification. On the other hand, for indicators with ZUSL – FC, MI, VI, and TVL – the more below the line the box plot, the more capable the indicator will be.

The indicator FC is capable of meeting the specifications, with 100 % of the points below the ZUSL, and the indicators OPC, TVL, and VI shall be the priority, once 11, 23, and 23 % of points, respectively, exceed the limit. As OPC, TVL, and VI are predictable (absence of special causes of variation) and do not meet the specifications, it leads to the conclusion that the specification limits are between the control limits (Oakland, 2003), according to those observed on individual charts in Figures 2A, D and F.

For MI and ME, acting on the causes of (special) points outside the control zone would be the first stage in improving the process. It is expected that certain indicators have special causes of variation when control charts are used which tend to decline as long as the standard operating procedures are updated and expanded (Montgomery, 2019). This should be sufficient to make them capable of meeting the specification since the points that did not reach the target were responsible for the special cause of variation.

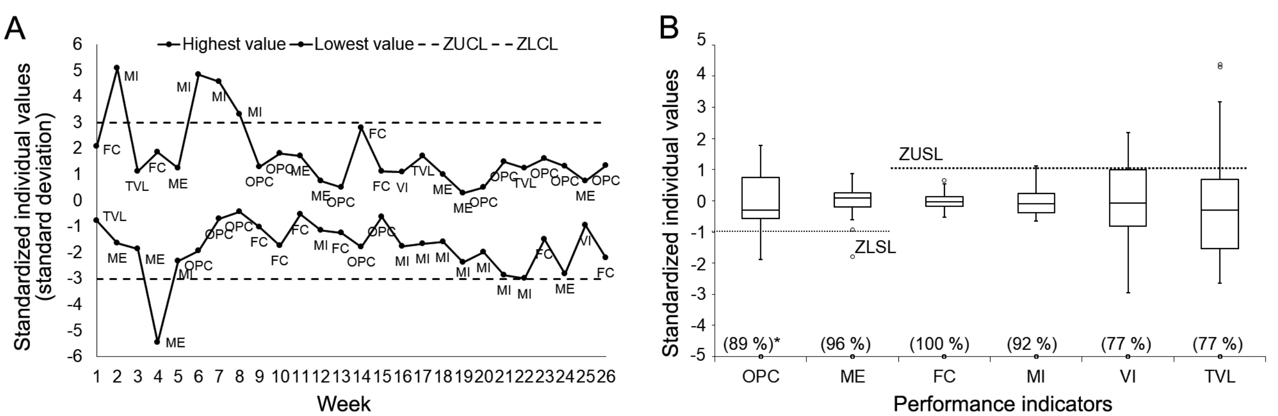

Figure 3 – Visualization of performance indicators of a sugarcane harvester operating during a season. (A) Standardized group control chart. (B) box plot of process capability with standardized scale (OPC = Operational processing capacity; ME = Managerial efficiency; FC = Fuel consumption; MI = Mineral impurities; VI = Vegetal impurities; TVL = Total visible losses; ZUSL = standardized upper specification limit; ZLSL = standardized lower specification limit; *Numbers in parentheses represent the percentage of points inside specification).

Since OPC, VI, and TVL are in statistical control but are not capable, it is the responsibility of the manager and team to investigate the influence exerted over these indicators and to act in a way to improve them to meet the specifications, making the process predictable. For example, a better balance between harvester and sugarcane yield could improve the performance of OPC (Ramos et al., 2016) or an increment in the rotation of the primary extractor yield better VI performance (Alcantara et al., 2017; Martins et al., 2017), or an increment in the speed of operation that improves the OPC but worsens TVL (Martins et al., 2017; Santos et al., 2014). Regardless of the action taken, it is important that all six indicators are monitored so that the optimum operation is achieved and not the optimum of one indicator only. This is the basis of the systemic method.

The standardized scale box plot can also be used to measure the overall effect of intentional process changes by visually comparing the performance of all KPIs before and after the intervention. This systemic view of the process is important because a change focused on improving one KPI can have an unwanted and unpredictable influence on the performance of another.

The method described in this article is based on retrospective analysis of historical data, where all samples are analyzed simultaneously, and can be replicated to support the management of mechanized agricultural operations if at least 20 samples are available. When historical data are not available or the number of samples is insufficient, the recommendation is to follow the theory of short production runs to adjust the control limits (Pyzdek, 1993).

This study covers the first phase of the control chart application that focuses on assisting mill technical staff in bringing the KPIs under statistical control. This may require several cycles of data collection, detection of assignable causes of variation by the control chart and corrections. Subsequently, new data is collected, control limits are revised and so on to the point where there is a performance process under control when reliable control limits can be calculated to monitor the indicator's performance in the future. Next, the second phase begins where the control chart is applied to monitor the performance indicator by comparing each successive sample, as soon as available, with the control limits (Oakland, 2003).

Conclusions

The joint use of standardized group control chart and box plot with standardized scale allows for the identification of special causes and process capability of a group of performance indicators in the same manner as several individual control charts.

The method does not present restrictions on the number of indicators and it can also be used to monitor diverse equipment simultaneously, simplifying the visualization and interpretation of KPIs. The simultaneous tracking of different KPIs, the systemic method, can help the manager to control and improve the sugarcane harvesting process.

A limitation of the standardized group control chart is its inability to indicate all changes in the level of any KPI as individual control charts do. Despite this limitation, the standardized group control chart is still a valuable tool to support the improvement of multiple performance indicators. As regards the indicators evaluated, the total visible losses and vegetal impurities do not show special causes of variation but a more restricted capacity to meet specifications.

Authors' Contributions

Conceptualization: Peloia, P.R.; Milan, M.; Romanelli, T.L.; Gimenez, L.M. **Data acquisition:** Peloia, P.R.; Milan, M. **Data analysis:** Peloia, P.R. **Design of methodology:** Peloia, P.R.; Milan, M. **Writing and editing:** Peloia, P.R.; Milan, M.; Romanelli, T.L.; Gimenez, L.M.

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