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## MONITORING TRACTOR PERFORMANCE USING SHEWHART AND EXPONENTIALLY WEIGHTED MOVING AVERAGE CHARTS

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### KEYWORDS

statistical process control, management operations, agricultural mechanization.

### ABSTRACT

Statistical process control has been widely used in agricultural operations for monitoring and improving process quality. This study aims to evaluate the Shewhart and exponentially weighted moving average (EWMA) control charts to monitor the performance of an agricultural tractor-planter set. The design is completely randomized based on the assumptions of statistical process control and comprises two treatments: day and night shift treatments. The data to assess the performance of the tractor-planter set are collected during the day and night shifts and used to evaluate the operating speed, motor rotation, engine oil pressure and water temperature, and hourly fuel consumption. The dataset comprised 40 samples compiled from the frontal monitor column inside a tractor cab. It is concluded that both Shewhart and MMEP/EWMA control charts can be used to evaluate engine performance based on the quality indicator parameters investigated, regardless of the normality assumption of the datasets.

### INTRODUCTION

The use of statistical process control in agriculture has been primarily disseminated through the use of individual control charts (Shewhart charts) and is regarded as an option for monitoring certain processes, analyzing results, and further decision-making regarding activities related to mechanized agricultural operations (Voltarelli et al., 2014).

Shewhart control charts have been used to evaluate the quality and stability of the mechanical harvesting of coffee (Tavares et al., 2015; Cassia et al., 2013; Reis et al., 2010) and soybean (Toledo et al., 2008), as well as in agricultural aviation (Reis et al., 2010). However, Shewhart charts cannot detect small variations and, therefore, are not suitable for evaluating quality indicators of agricultural machines with low coefficients of variation, such as data from tractor engines collected by sensors placed at specific locations that are monitored in real time through telemetry (Voltarelli et al., 2015).

In these cases, exponentially weighted moving average (EWMA) charts are used because they can detect

minute variations during the process and indicate whether the evaluated process is unstable or stable. It is noteworthy that this chart plots the exponentially weighted averages; therefore, the normal distribution of the dataset is not a requirement, as opposed to individual value (Shewhart) control charts, which require a normal distribution of the dataset (Montgomery, 2016).

The data may show less variation because the quality indicators are measured by sensors placed on the motor. Therefore, it is important to monitor the process using two control chart models to rectify and to implement preventive and/or corrective maintenance to increase the useful life of the tractor engine (Voltarelli et al., 2015).

Hence, this work aims to evaluate and compare Shewhart and EWMA charts to monitor the performance of an agricultural tractor-planter set based on the assumption that different chart models used to monitor the process may present different results, thereby rendering the decision-making regarding agricultural operations more difficult.

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## MATERIAL AND METHODS

The experiment was conducted in an agricultural area planted with sugarcane in Monte Alto, SP, in March 2013. The mechanized planting of sugarcane was performed using a tractor-planter set comprising a John Deere tractor model 7715 4x2 TDA, with 136.0 kW engine power at 2,200 rpm, six cylinders, 17:1 compression ratio, and 600/65R28 and 710/70R38 front and rear billets, respectively, both R1W. During the mechanical planting of sugarcane, the tractor was operated with the gauge adjusted to 2.70 m and a 1B operating gear.

The two-row chopped sugarcane planter used, Tracan model PTX 7010, can plant six to seven tons of seedlings, 10,540 kg mass, a 1,300 kg fertilizer reservoir, 3.60 m wide, 600/50 22.5 rotated, with furrow rods spaced 1.50 m. The planter was regulated to a planting depth of 0.30.

The experimental area was cultivated with sugarcane under a conventional tillage system for 6 years. After that period, the sugarcane ratoons were removed, and the soil was treated using a conventional tillage system (medium and light harrowing) after subsoiling at a depth of 0.60 m. Subsequently, soybean was sown, and after harvesting, sugarcane was planted mechanically without prior soil preparation.

The experimental design was completely randomized based on the principles of statistical process control and comprised two treatments, i.e., day and night shift treatments. The performance of the tractor-planter set was evaluated during the day (from 3:30 p.m. to 5:30 p.m.) and night (from 7:30 p.m. to 9:30 p.m.) shifts, with 40 samples/datasets being collected for each shift (one sample every 3 min).

The evaluated quality indicators were as follows: operating speed, motor rotation, engine oil pressure and water temperature, and hourly fuel consumption. These data were measured by sensors installed on specific locations of the motor and read/collected in real time in the front column monitor (Command Center™) inside the tractor cab. Only one evaluator measured all readings inside the tractor cabin.

The initial analysis involved obtaining the descriptive statistics of the data to determine the general behavior of the dataset using dispersion measures (i.e., the amplitude, standard deviation, and coefficient of variation). Data normality was verified using the Ryan-Joiner test,

which measures how well the sampled data follow a normal distribution (Noiman et al., 2013).

Furthermore, the results were evaluated using statistical process control and individual value control charts (Shewhart). These charts have a central line indicating the general mean, and two more lines indicating the upper and lower control limits (UCL and LCL), respectively, calculated based on the standard deviation of the variables (mean plus and minus three times the standard deviation, respectively, when greater than zero) (Montgomery, 2016). Voltarelli et al. (2015) stated the unsuitability of using the individual value control chart for monitoring agricultural processes, regardless of data normality assumption.

The EWMA was calculated based on the methodology described by Montgomery (2016) using measured parameter values, process target measurement, and a smoothing factor such that the sample dataset is arranged around the average line of the control chart.

The UCL and LCL of the EWMA chart were set for a bandwidth of three (distance between the mean and the control limits) with the smoothing factor set to  $\lambda = 0.4$ , based on the recommendation of Montgomery (2016) for comparing control charts. The EWMA chart can be used as a process monitoring tool to determine whether the data are normally distributed because a normal distribution is not a prerequisite.

## RESULTS AND DISCUSSION

The operating speed, motor rotation, engine oil pressure and water temperature, and hourly fuel consumption data collected during the day and night shifts of mechanical sugarcane planting (Table 1) cannot be described by the normal probability density function, according to the Ryan-Joiner test. The results showed non-normal distributions of the dataset, as evidenced by the value greater than zero obtained from the normality test.

Except for hourly fuel consumption, whose coefficient of variation can be considered as average, the other parameters exhibited low (< 12%) and very low (< 10%) coefficients of variation, according to the classification of Warrick & Nielsen (1980).

TABLE 1. Descriptive statistics of performance indicators of sugarcane tractor-planter set as a function of operating shifts.

Quality indicators	Day shift				Night shift			
	A*	$\sigma$	CV	RJ	A*	$\sigma$	CV	RJ
WS (km h <sup>-1</sup> )	0.30	0.06	1.20	0.982 <sup>A</sup>	0.60	0.10	1.89	0.839 <sup>A</sup>
MR (rpm)	90.00	19.01	0.88	0.919 <sup>A</sup>	80.00	16.80	0.78	0.982 <sup>A</sup>
EOP (kPa)	40.00	11.54	3.08	0.998 <sup>A</sup>	84.00	14.85	3.98	0.906 <sup>A</sup>
EWP (°C)	8.00	2.49	3.03	0.984 <sup>A</sup>	5.00	1.55	1.91	0.993 <sup>A</sup>
HfC (L h <sup>-1</sup> )	20.10	3.89	14.49	0.954 <sup>A</sup>	21.60	3.65	14.35	0.959 <sup>A</sup>

WS - operating speed; MR - motor rotation; EOP - engine oil pressure; EWT - engine water temperature; HfC - Hourly fuel consumption; \* A - Total amplitude;  $\sigma$  - Standard deviation; CV (%) - Coefficient of variation; RJ - Ryan-Joiner normality test value (N: normal distribution -  $p > 0.05$ ; A: non-normal distribution -  $p < 0.05$ ).

The association of the performance indicator parameters with low and very low coefficients of variation with the amplitude and standard deviation values indicates the dispersion of the dataset. This result is satisfactory because the measurements were performed by sensors and the variation should be the smallest possible to represent the tractor engine monitoring more accurately.

The motor rotation and engine water temperature varied the most during the day shift. The motor rotation might be affected by the seedling load in the planter and soil resistance to furrowing, whereas the engine water temperature was affected by the varying intensity of the solar radiation.

The standard deviation and coefficient of variation for the operating speed and hourly fuel consumption were lower during the daytime shift than those in the night shift. This implies that monitoring the tractor engine in the night

shift is more difficult owing to the insufficient management and poor visibility of the mechanical set traffic in the field.

The comparison of the Shewhart and EWMA control charts shows outliers in the operating speed (Figure 1) in both the day and night shifts. This demonstrates specific causes that affected the operation, whereas the average operating speed was  $5.3 \text{ km h}^{-1}$ .

The low standard deviation values decreased the UCL and LCL, particularly for the EWMA control chart. However, these limits deviated more from the average in the night shift because of the outlier, i.e., observation 13 above the upper control limit in the Shewhart chart, and observations 13 and 14 in the EWMA control chart. A possible explanation for these instabilities can be inferred by the terrain slope at this point, i.e., when the mechanical set gained speed, by extrapolating the UCL.

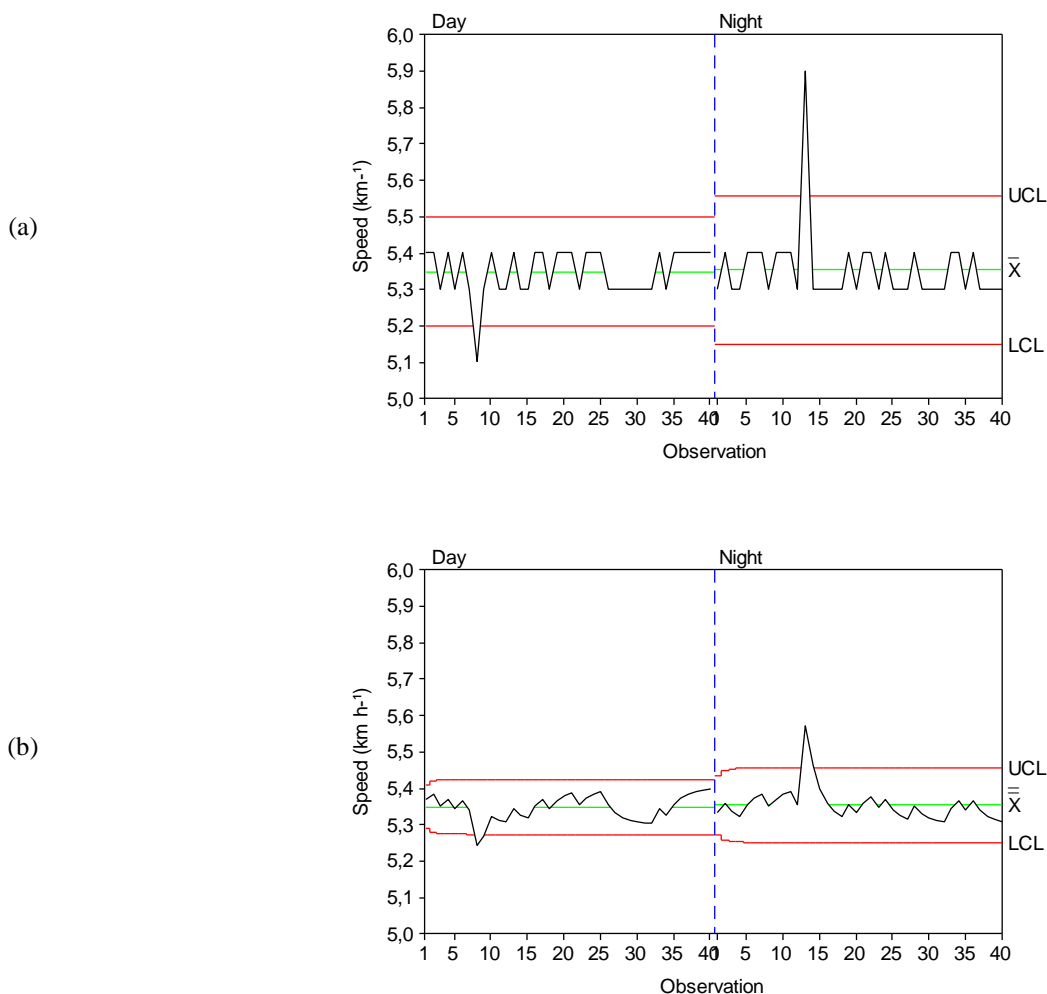


FIGURE 1. Control charts for individual values (a) and exponentially weighted moving average (b) for operating speed. UCL: Upper control limit, LCL: Lower control limit,  $\bar{X}$ : average of individual values,  $\bar{\bar{X}}$ : exponentially weighted moving average.

Meanwhile, during the day shift, the outlier (observation 8) in the Shewhart chart (observations 8 and 9 for EWMA chart) resulted in process instability. This instability observed in both control charts may have resulted from the fact that the planting area was near the head of a level curve, where the soil compaction was higher owing to the more intense traffic of machinery for building the curve and the greater number of maneuvers on the site. Therefore, the soil conditions demanded more power from

the tractor-planter set owing to the greater soil resistance offered to the planter furrowing mechanisms.

However, because data normality was not required, the Shewhart and EWMA control charts can be used to monitor the operating speed variable because the observed variations were negligible, i.e., 0.10, and  $0.30 \text{ km h}^{-1}$  for the UCL and LCL, respectively. These minute variations impaired the quality of the mechanical set operation, thereby affecting the planting quality. It is noteworthy that even though the EWMA control chart had a higher number

of outliers, it was as effective as the Shewhart chart, thereby reducing inference on the operation quality level.

The individual chart for motor rotation in the day shift indicated values that were approximately the general mean (Figure 2), incurred in non-random causes, as evidenced by observations 8 and 26 below the LCL. Subsequently, observation 8 can be correlated to the control chart for the operating speed in the day shift because the speed reduction can be associated with the decrease in engine

rotation, indicating that the greater soil resistance evidenced by the tractor–planter at this site demanded more engine power. Meanwhile, during the night shift, the process remained stable and/or varied only with the natural causes.

The next outlier (observation 26), as evidenced in the Shewhart chart, is attributable to the soil resistance as well as the loading of billets in the planter during planting, which was overcome by the power of the planting set but caused a significant decrease in the motor rotation.

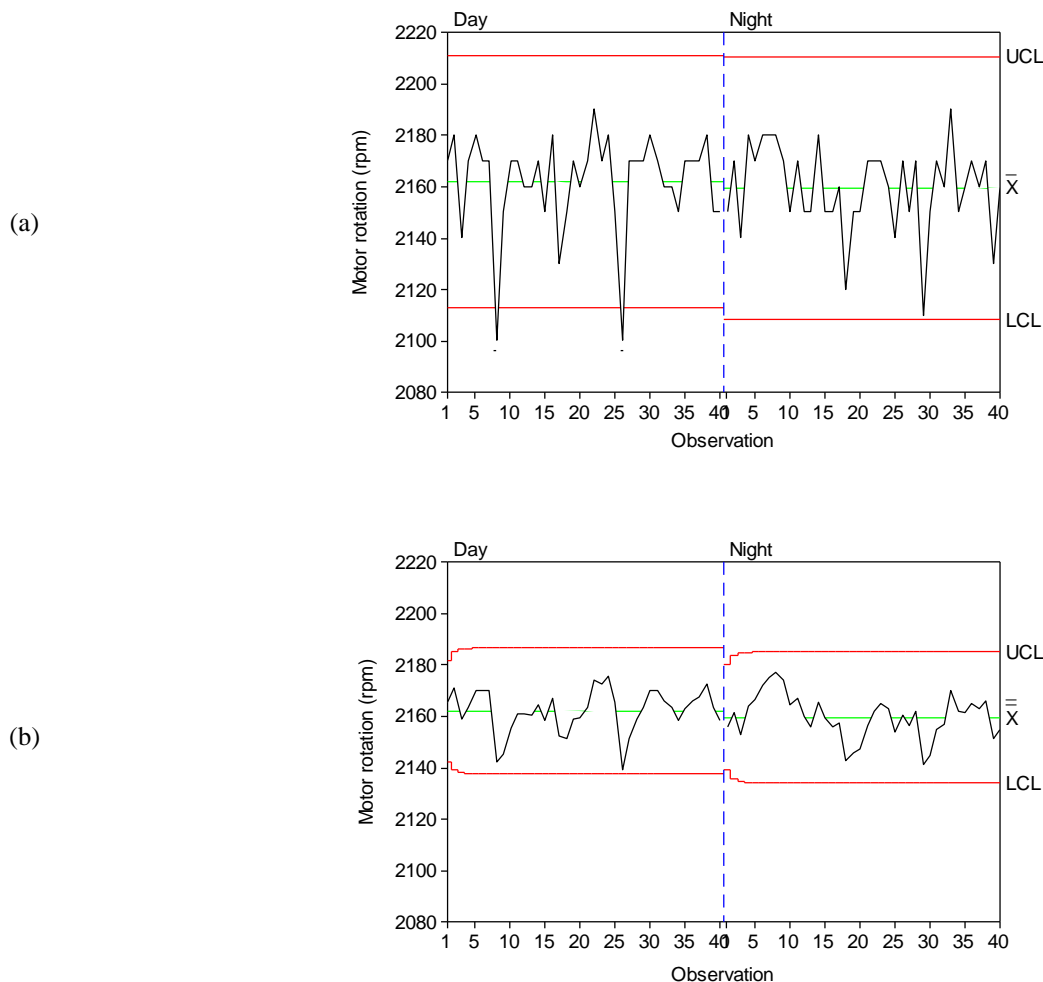


FIGURE 2. Control charts for individual values (a) and exponentially weighted moving average (b) for motor rotation. UCL: Upper control limit, LCL: Lower control limit,  $\bar{X}$ : average of individual values,  $\bar{X}$ : exponentially weighted moving average.

It is noteworthy that the engine speed varied between 2.100 and 2.200 and from 2.140 to 2.180 rpm for the Shewhart and EWMA control charts, respectively, with an average of 2.160 rpm, which was approximately the maximum rotation power of the engine (2.200 rpm). At the maximum motor rotation, the hourly fuel consumption increases and torque decreased. However, for this operation, the sugarcane planter required more power to be pulled; as such, the tractor–planter set was operated similar to the optimum engine operating conditions.

Kim et al. (2011) stated that tractors operating at their maximum engine revolutions demanded high fuel consumption, but the tractors would use all of its available power. Similarly, Ripoli & Ripoli (2010) investigated the performance of mechanical sugarcane planting in Brazil and reported similar results.

Meanwhile, the analysis of the EWMA control chart showed that motor rotation remained steady in both

shifts, indicating a stable process with 100% of the data points between the UCL and LCL.

A comparison of the two charts for the daytime shift showed that the EWMA chart indicated a more stable process compared to the Shewhart chart, as can be explained by the fact that although the EWMA detected small variations, they were insufficient to reflect process instability.

It is noteworthy that for motor rotation, the control limits of the individual value and moving average charts ranged from 30 to 20 rpm, respectively, a typical variation interval considering the effort subjected to the engine during such an operation. In this sense, the non-normality condition of the dataset accepted by the EWMA is no longer an advantage because the Shewhart charts can also efficiently determine process quality and the limiting conditions that may render it unstable.

The individual charts show that the engine oil pressure (Figure 3) was unstable, as verified by observations 38 and 29 in the daytime and nighttime shifts, respectively.

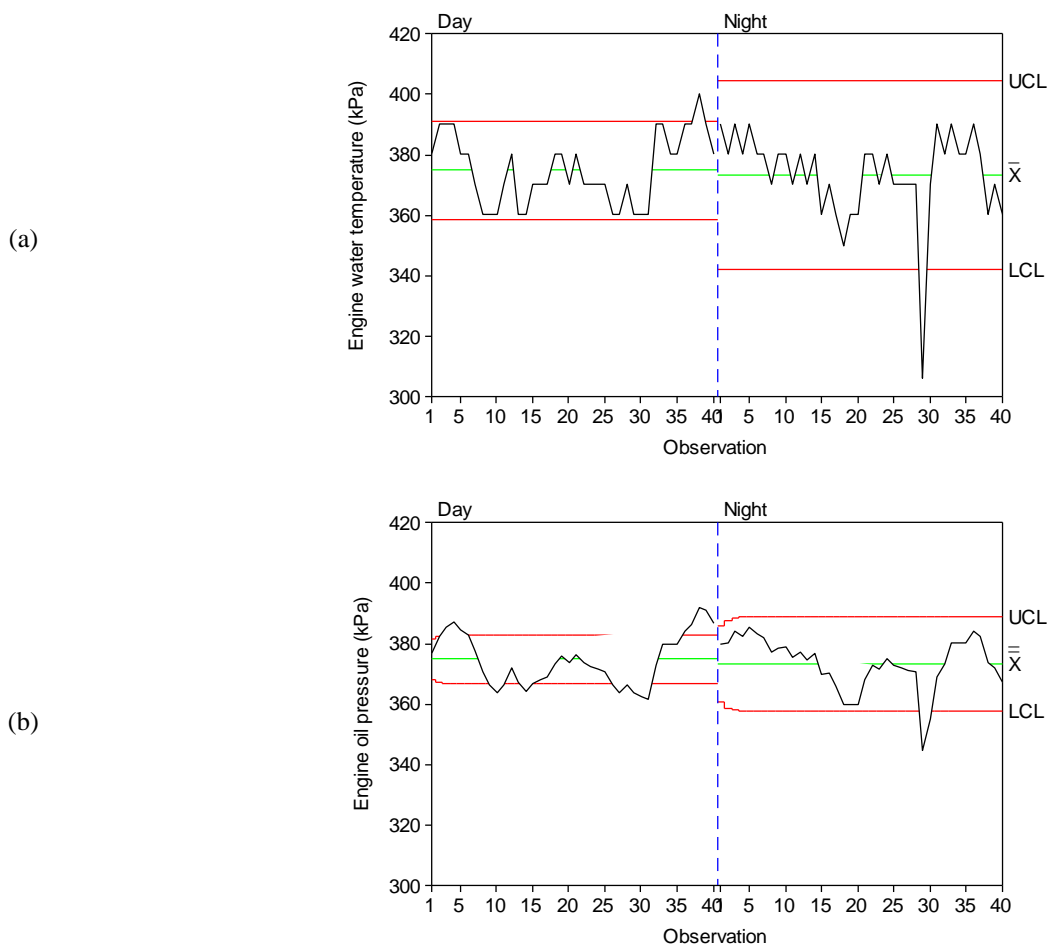


FIGURE 3. Control charts for individual values (a) and exponentially weighted moving average (b) for engine oil pressure. UCL: Upper control limit, LCL: Lower control limit,  $\bar{X}$ : average of individual values,  $\bar{\bar{X}}$ : exponentially weighted moving average.

These instabilities might have occurred because the microscopic oil filter cannot filter all the pumped oil. In addition, the pressure regulator valve might have remained in the closed position longer than necessary or increased the pressure or opening for a long time, thereby preventing the oil from being pumped to the engine and causing most of the oil to return to the crankcase. Other factors affecting this variable might be low crankcase oil level and clogged return pipe due to excess contamination.

Moreover, the factors above may have caused the outliers in the EWMA chart that was caused by the increasing (day shift: observations 3, 4, 5, 36, 37, 38, 39, and 40) and decreasing (day shift: observations 9, 10, 11, 14, 15, 26, 27, 28, 29, 30, and 31; and night: observations 69 and 70) oil pressure during the monitoring of the operation.

The two charts exhibited similar behaviors of engine oil pressure during the process, regardless of the higher number of outliers for the EWMA (Figure 3b) during the night shift (45%) as time progressed. Meanwhile, the Shewhart chart exhibited only 2.5% of outliers in the night shift.

This shows that the number of outliers varied depending on the control chart; however, this variation is typical in agricultural machinery engines, according to Grisso et al. (2008). Agricultural engines are operated by circulation under pressure due to the long distance and several galleries covered by the oil inside the engine; the pressure may vary from 103 to 275 kPa in most tractors, reaching up to 448 kPa in certain situations.

Furthermore, the comparison of oil pressure values obtained in this study with the variation interval described by Grisso et al. (2008) shows that the tractor engine was operated close to its extreme condition, requiring more power from the oil pump to force oil displacement to the engine galleries. However, the outliers above the UCL did not exceed 448 kPa in both control charts; this might impose a risk to the engine lubrication because the oil pump would not be able to pump the oil into the engine.

The engine water temperature (Figure 4) had a higher standard deviation in the day shift compared with in the night shift, as shown by the UCLs and LCLs in the individual value charts. The engine water temperature oscillated during the night shift but did not affect the quality of this indicator. Bennett (2009) monitored the water temperature of a tractor engine operating with diesel and concluded that the oscillations observed reflected the operation of the engine cooling system; furthermore, it was reported that temperature variations were typical owing to the dynamism of this system.

Therefore, based on the concepts of the cooling system, the outliers may indicate that the engine cooling system is operating well. The thermostatic valve opens when the engine temperature is between 85 °C and 94 °C (Cemagref, 1986), causing water to flow through the entire cooling system, including the engine, to dissipate heat, decrease the temperature, and avoid damage to the machine.

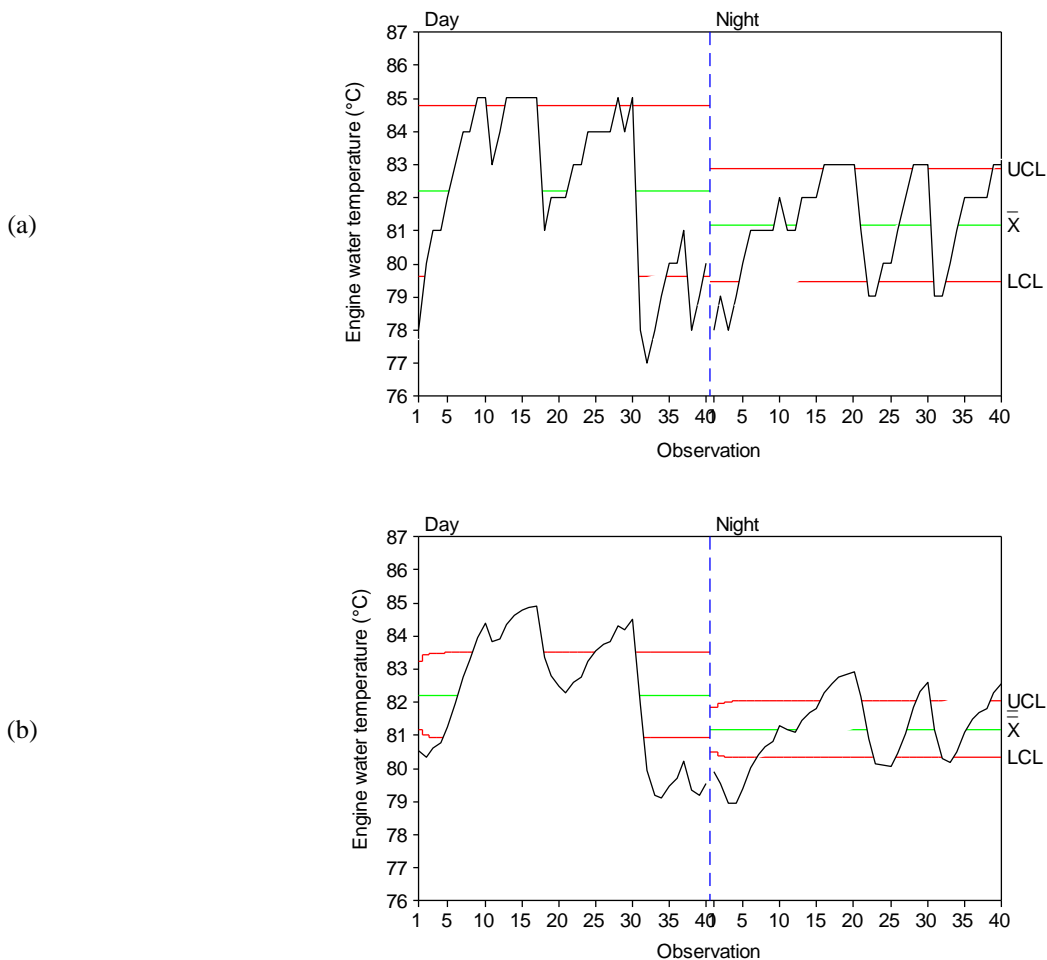


FIGURE 4. Control charts for individual values (a) and exponentially weighted moving average (b) for engine temperature. UCL: Upper control limit, LCL: Lower control limit,  $\bar{X}$ : average of individual values,  $\bar{\bar{X}}$ : exponentially weighted moving average.

The individual value charts in Figure 4a show temperature increases that caused the thermostatic valve to open and successfully cool the engine temperature. Grisso et al. (2008) studied tractors with different horsepowers under several conditions (different engine speeds/motor rotation) and reported that engine cooling should not exceed the average temperature of 88 °C at high engine rotations regardless of the horsepower. Similarly, Shin et al. (2012) monitored engine water temperature and reported a mean temperature ranging from 82 °C to 83 °C, which describes the full function of the system.

The Shewhart chart had 40% and 45% of outliers, whereas the EWMA chart had 70% and 52% of outliers for the day and night shifts, respectively. However, the number of false alarms for the outliers was not higher for the individual control charts; therefore, these charts can be

used for monitoring the water temperature, and normality was not necessary, enabling the process analyst to be aware of the process.

The EWMA chart had a higher number of outliers extrapolating the lower (15% day shift and 7% night shift) and upper (15% day shift) control limits compared with the Shewhart chart. The latter did not exhibit values that can disrupt the operation of the cooling system and engine. It is noteworthy that a higher precision of the analysis tool enables a higher number of outliers to be detected.

The hourly fuel consumption (Figure 5) had the highest amplitude interval between the control limits (UCL and LCL) but deviated from the average value (Shewhart and EWMA charts). This was observed for the night shift, but the process was considered unstable for both the day and night shifts (observations 32 and 6, respectively).

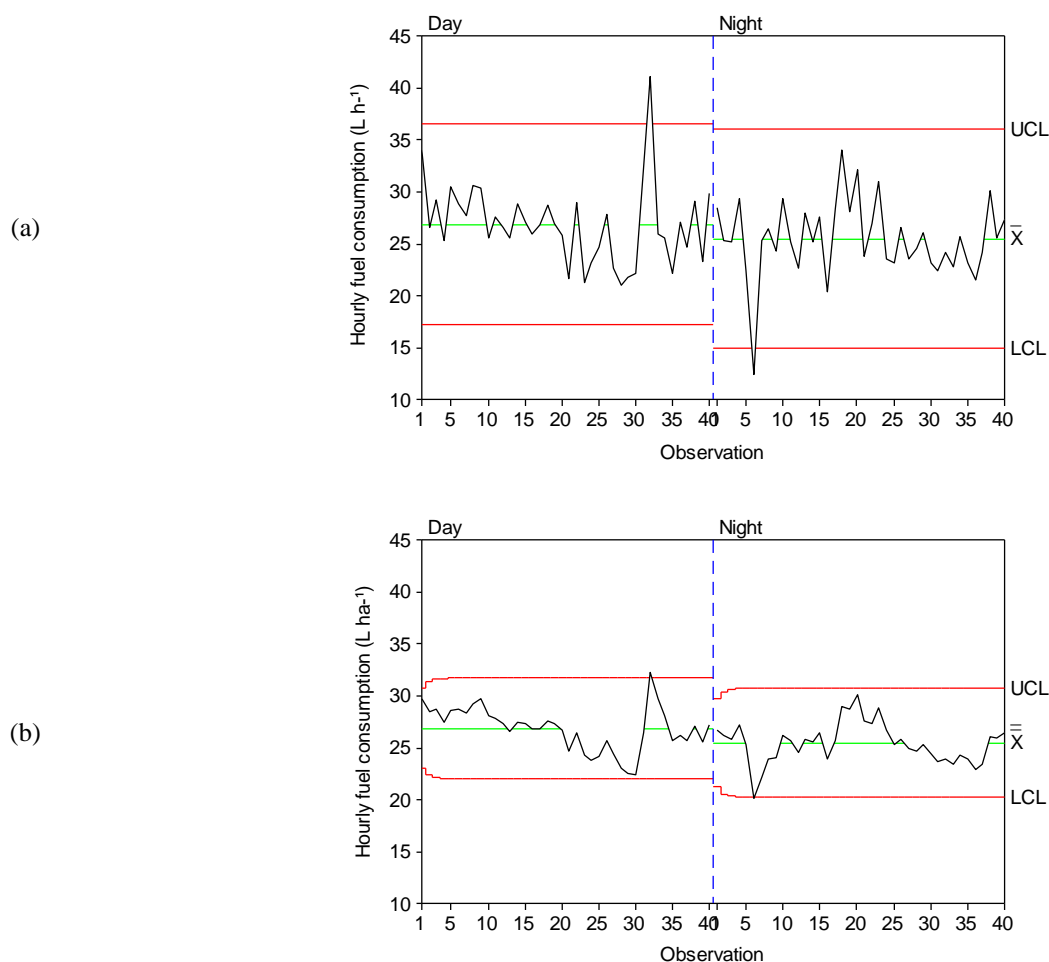


FIGURE 5. Control charts for individual values (a) and exponentially weighted moving average (b) for hourly fuel consumption of mechanical set. UCL: Upper control limit, LCL: Lower control limit,  $\bar{X}$ : average of individual values,  $\bar{\bar{X}}$ : exponentially weighted moving average.

The outliers indicate the presence of special causes during the operation, resulting in process instability; this was observed during the daytime shift when the planter was loaded with billets. The heavier load increased fuel consumption per hour until the engine speed stabilized and the operation returned to normal.

Meanwhile, the outlier below the LCL in the night shift can be explained by the smaller seedling load transported by the planter that decreased the traction force necessary to move the mechanized set, consequently decreasing the hourly fuel consumption. The hourly consumption of the fuel may vary depending on the operating speed, motor rotation, operating gear, and quantity of billets inside the sugarcane planter container because the fuel consumption is higher for greater transported weights, among others.

Grisso et al. (2008) concluded that the ability to predict fuel consumption and engine power in several operations can be important because these parameters affect the production costs and may facilitate in dimensioning the operations.

Both control charts show that observations 32 and 6 were outliers that extrapolated the UCL and LCL, respectively. This result may indicate that when outliers

deviate from the average values and other observations, no significant evidence exists that can favor either one of the control charts because their performances become similar.

## CONCLUSIONS

The performances of the individual value (Shewhart) and EWMA control charts varied according to the parameters evaluated.

Motor performance parameters can be evaluated by both the Shewhart and EWMA control charts, regardless of the normality assumption of the datasets.

Furthermore, using control charts as a tool to evaluate process quality should be tested in other mechanized agricultural processes, while considering the fact that the ability of the evaluator to fully interpret the results, describe process behavior, and understand the process is fundamental for analyzing and determining process quality.

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