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QUALITY OF MECHANICAL SOYBEAN HARVESTING AT TWO TRAVEL SPEEDS

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ABSTRACT: Soybean harvesting is the last operation performed in the field and therefore has high added value. Quantitative losses during this process should therefore be minimized to achieve maximum quality and increase the sustainability of the production system. The aim of the present study was to determine and characterize the quantitative losses and operational characteristics of an axial-flow combine harvester, using tools from Statistical Quality Control to determine the quality of the harvesting operation. The experiment was designed in accordance with the assumptions of statistical process control, with a total of 40 sampling points monitored over time. Quality indicators of harvester performance and crop agronomic characteristics were evaluated at two harvester travel speeds (5 and 7 km h^{-1}). The stability of the process was confirmed for the variables indicated by the analysis of run charts for the variables engine water temperature at a travel speed of 5 km h^{-1}; engine oil pressure, fuel consumption and cutting height at a travel speed of 7 km h^{-1}; and losses at both speeds, indicating that these were only affected by natural causes.

KEYWORDS: control charts, variability, harvesting losses.

INTRODUCTION

Soybean (*Glycine max*. (L.) Merril) is an extremely important crop for the Brazilian economy, with more than 33 million hectares planted in the 2016-2017 harvest and an estimated production of greater than 107 million tons (CONAB, 2017). Because soybean is a fully mechanized crop, losses commonly occur during harvest. These losses are influenced by both factors inherent to the crop and factors related to the harvesters (Cunha et al., 2009). The regulation of harvesters is an important factor of harvest mechanization and is directly related to crop characteristics, such as seed quality (Silva et al., 2013a), grain moisture content, pod dehiscence, inadequate sowing, wrong cultivar selection, weed occurrence, and poor crop development, among others (Toledo et al., 2008). Some of the main adjustments performed at harvest concern the harvester travel speed, track system rotation and opening, reel rotational speed, and cleaning system cooling fan speed (Chioderoli et al., 2012; Carvalho & Novembre, 2012).

Losses from mechanical harvesting decrease the profitability of harvesting and farming operations, as harvesting is the final operation in the production process, when crops exhibit the highest added value (Tabile et al., 2008). Decreasing soybean mechanical harvesting losses is therefore necessary to increase the economic return of soybean production (Magalhães et al., 2009; Toledo et al., 2008).

Loss monitoring to improve the quality of soybean harvesting operations can be performed using the tools of Statistical Quality Control (SQC). Using SQC in agricultural operations helps achieve results closer to the desired standards, as the main SQC hypothesis is that quality is assured by decreasing the variability of the main characteristics of a given process (Silva & Voltarelli, 2015).

In recent years, various authors have used quality indicators to monitor mechanical harvesting using Statistical Process Control (SPC), one of the tools of SQC. Most studies used control charts to identify the occurrence of special causes (Cassia et al., 2013, 2015; Silva et al., 2013b; Zerbato et al., 2013; Voltarelli et al., 2013, 2014, 2015; Noronha et al., 2011; Custodio et al., 2012). Chioderoli et al. (2012) reported that control charts can be used efficiently to evaluate the quality of

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the soybean harvesting process. The authors tried to quantify losses and evaluate harvester operational characteristics using SPC and concluded that grain losses caused by the harvester were outside control limits but within acceptable standards for soybean. The authors also stated that the quality of the harvest operation and harvester adjustments varied with travel speed, with higher losses being observed for the lowest speeds tested.

Loureiro Junior et al. (2014) used SPC to analyze the variability and viability of using different sampling areas (1, 2 and 3 m²) to quantify losses in soybean mechanical harvesting. They observed that losses in the harvester were stable, whereas the plant cutting and total losses exhibited unstable behavior. They also concluded that the frame size did not affect the quantification and variability of losses in soybean mechanical harvesting and that a 1 m² frame can be used to determine losses.

Paixão et al. (2017) also used SPC, with cumulative sum (CUSUM) control charts, to evaluate the quality of soybean mechanical harvesting in irregular, trapezoidal and rectangular plots, monitoring harvester activities and determining harvesting losses. The authors concluded that irregular plots indicated process stability throughout the evaluation period and that using CUSUM control charts provides greater rigor to the analysis of the process because of its calculation base.

Considering that harvesting losses may vary over time and that control charts may be used to evaluate the quality of harvesting operations at different harvester travel speeds, the aim of the present study was to determine the quantitative losses and operational characteristics of a soybean axial-flow combine harvester operating at two travel speeds, using SPC to determine the quality of the harvesting operation.

MATERIAL AND METHODS

The present study was performed in the state of Minas Gerais, municipality of Sacramento, in a soybean plantation of cultivar MSOY-8757 (MONSOY SEMENTES). The region’s climate is Cwa according to the Köppen climate classification, defined as subtropical humid with dry winters and hot summers.

The harvest was performed between the hours of 10:00 and 17:00 using an axial-flow combine harvester, Case IH model 81290, with a 331 kW (450 cv) engine, equipped with a 12.2 m-wide draper platform, a straw chopper, a chaff distributor and a performance monitor (AFS Pro 700), which was used to collect machine specifications and performance variables, such as the engine rpm, oil pressure and temperature, rotor speed, travel speed, fuel consumption and the concave clearance. The experiment was designed in accordance with the assumptions of SPC, with a total of 40 sampling points distributed in an irregular grid. The sampling points were marked based on the time of harvest, and data were collected every 10 minutes with a transverse spacing of 12 m. The harvester’s average travel speed was 5.0 km h^{-1} for the first 20 sampling points and 7.0 km h^{-1} for the remaining 20 sampling points.

The crop was characterized by measuring the first pod insertion height in 15 plants chosen randomly within the harvested area using a millimeter ruler. The cutting height was measured from the ground on 5 plants chosen randomly at each sampling point using a millimeter ruler (Chioderoli et al., 2012).

Soybean grain yield was determined by randomly collecting plants from 4 sowing rows, threshing the plants to determine grain weight, and extrapolating the weights to kg ha^{-1} (13% wet basis) (Compagnon et al., 2012).

Harvest losses were determined using 3 circular frames of area 0.33 m^2 covered with a shading screen (Sombrite), resulting in a joint area of 1.00 m^2 for each sampling point. The frames were dropped to the ground immediately after the passage of the harvester platform at predetermined points such that two frames were placed outside the harvester wheel tracks (to the left and right) and one between the wheel tracks (Paixão et al., 2017).

All grains found inside and under the frames after the passage of the harvester were collected and weighed. Grain found under the frames was classified as losses in the reel and due to deficiency in cutting height (GLRH). Grain found inside the frames was classified as losses in the track and cleaning systems (GLTC). The total grain losses (TGL) were calculated as the sum of GLRH and GLTC, expressed in kg ha^{-1}. When whole pods were found, the grain was threshed and quantified within the respective classifications. The grain moisture content was corrected to 13% using a correction factor for all sampling points.

The overall behavior of the data set (independent of the travel speed) was analyzed using descriptive statistics. The arithmetic mean, median, maximum, minimum, standard deviation and coefficients of variation, skewness and kurtosis were calculated. Data normality was tested using the Anderson Darling test.

The harvesting operation quality was evaluated using run charts and control charts for individual values. All quantified variables were used as SPC quality indicators (Silva & Voltarelli, 2015). In control charts for individual values, the lines plotted are the overall mean and mean range (center line) and the upper and lower control limits (UCL and LCL, respectively) calculated based on the standard deviation (the UCL is calculated as the mean plus three times the standard deviation; the LCL is calculated as the mean minus three times the standard deviation, when greater than zero). Run charts are graphical displays of data that allow one to monitor the expected mean over time and to search for patterns (clustering, mixture, trend and oscillation) that may indicate the presence of special causes affecting the process.

RESULTS AND DISCUSSION

The average grain moisture content was 12.5%. This value is considered ideal, with the recommended grain moisture content for soybean mechanical harvesting being between 12.0 and 15.9% because it minimizes losses and mechanical damage (Carvalho & Novembre, 2012).

The measures of position (mean, median and range) indicated normal distributions for all variables (Table 1). This was confirmed by the low coefficients of variation (CVs) observed for all variables except for cutting height and grain yield, which indicated a medium CV, and grain losses, which revealed a very high CV. CVs of 0 to 10% are considered low, CVs of 10 to 20% are considered medium, CVs of 20 to 30% are considered high, and CVs above 30% are considered very high (Pimentel-Gomes & Garcia, 2002). This is in accordance with Toledo et al. (2008) and Chioderoli et al. (2012), who also observed a high CV for harvesting losses.

TABLE 1. Descriptive statistical analysis for quality indicators of soybean mechanical harvesting.

Variable	Descriptive statistics								
	Mean	Median	Range	Standard deviation	Coefficients			p	Test
					CV (%)	Cs	Ck		
Engine rpm (rpm)	2083.3	2090.0	130.0	28.70	1.38	-2.09	4.58	<0.005	A**
Engine oil pressure (°C)	468.2	470.0	20	5.00	1.07	-0.36	0.57	<0.005	A
Engine water temperature (°C)	90.6	91.0	12.0	2.56	2.83	-2.83	8.84	<0.005	A
Fuel consumption L h^{-1})	85.0	87.0	19.9	4.98	5.86	-0.78	-0.08	0.011	A
Rotor speed (rpm)	588.0	580.0	100.0	30.98	5.27	0.77	-0.95	<0.005	A
Cutting height (cm)	11.7	11.7	9.2	2.23	19.04	-0.28	-0.35	0.511	N*
Grain moisture content (%)	12.5	12.5	0.3	0.08	0.6	0.38	-0.05	<0.005	A
GLRH*** (kg ha^{-1})	17.1	14.0	63.2	15.28	89.53	1.97	4.01	<0.005	A
GLTC**** (kg ha^{-1})	8.2	7.7	25.5	4.89	59.57	1.07	2.92	0.151	N
Total grain losses (kg ha^{-1})	25.3	21.7	65.5	15.91	62.94	1.52	2.34	<0.005	A
Grain yield (kg ha^{-1})	2616.0	2664.0	847.2	332.40	12.71	0.42	-0.47	0.230	N

Ck: Coefficient of kurtosis; Cs: Coefficient of skewness; *N: Normal distribution according to the Anderson‑Darling test ($p<0.05$); **A: Non-normal distribution; *** Grain losses in the reel and due to deficiency in cutting height; **** Grain losses in the track and cleaning system.

For all types of losses evaluated, points were more concentrated around values lower than the mean (positive coefficients of skewness and kurtosis) (Table 1), thus indicating that a large fraction of losses were less than the mean. However, the data variability was high, as indicated by the high range, standard deviation and CV values, and the distance between the mean and the median indicated non-uniformity and high variability of losses. This was also reported by Toledo et al. (2008).

Regarding the variables directly related to plants, the cutting height exhibited a greater concentration of values above the mean (negative coefficients of skewness and kurtosis), indicating that the harvester cutting height was higher most of the time but still less than the average first pod insertion height, which was 18.7 cm. This resulted in low mean grain losses in the reel and due to deficiencies in the cutting height (17.1 kg ha^{-1}; 0.65%). The observed mean cutting height was less than those reported by Chioderoli et al. (2012) and de Pereira Júnior et al. (2010) for soybean mechanical harvesting (0.14 m and 0.15 m, respectively). The remaining variables directly related to plants (grain moisture content and yield) exhibited low coefficients of skewness and kurtosis, indicating concentrations of values above the mean.

The Anderson-Darling test found data normality only for cutting height, grain yield and grain losses in the track and cleaning systems, indicating more uniform variation. The other variables exhibited non-normal distributions (Table 1). Although most variables exhibited skewed distributions, it is worth noting that normality, while desirable, is not essential for application of SPC (Samohyl, 2009).

The run charts showed no pattern – indicating process stability - for cutting height, engine oil pressure and fuel consumption for the 7 km h^{-1} travel speed, engine water temperature for 5 km h^{-1}, and grain losses for both speeds (Table 2). The remaining variables showed at least some type of pattern, which will be discussed together with the control charts.

TABLE 2. Run chart probability values for quality indicators evaluated for soybean mechanical harvesting.

Soybean harvest					
Quality indicators	**Travel speed**	**Patterns**			
		C	**M**	**T**	**O**
Engine rpm	5 km h^{-1}	0.519^{ns}	0.481^{ns}	**0.048***	0.952^{ns}
	7 km h^{-1}	0.916^{ns}	0.084^{ns}	0.987^{ns}	**0.013***
Engine oil pressure	5 km h^{-1}	**0.001***	0.999^{ns}	**0.000***	1.000^{ns}
	7 km h^{-1}	0.631^{ns}	0.369^{ns}	0.500^{ns}	0.500^{ns}
Water temperature	5 km h^{-1}	0.716^{ns}	0.284^{ns}	0.500^{ns}	0.500^{ns}
	7 km h^{-1}	0.383^{ns}	0.617^{ns}	**0.048***	0.952^{ns}
Fuel consumption	5 km h^{-1}	**0.001***	0.989^{ns}	0.500^{ns}	0.500^{ns}
	7 km h^{-1}	0.677^{ns}	0.323^{ns}	0.500^{ns}	0.500^{ns}
Rotor speed	5 km h^{-1}	**0.001***	0.999^{ns}	**0.048***	0.952^{ns}
	7 km h^{-1}	0.976^{ns}	**0.024***	0.500^{ns}	0.500^{ns}
Cutting height	5 km h^{-1}	**0.011***	0.989^{ns}	0.500^{ns}	0.500^{ns}
	7 km h^{-1}	0.677^{ns}	0.323^{ns}	0.500^{ns}	0.500^{ns}
Grain moisture content	5 km h^{-1}	**0.011***	0.989^{ns}	**0.013***	0.987^{ns}
	7 km h^{-1}	1.000^{ns}	**0.000***	**0.000***	1.000^{ns}
GLRH** (kg ha^{-1})	5 km h^{-1}	0.179^{ns}	0.821^{ns}	0.867^{ns}	0.133^{ns}
	7 km h^{-1}	0.677^{ns}	0.323^{ns}	0.867^{ns}	0.133^{ns}
GLTC*** (kg ha^{-1})	5 km h^{-1}	0.500^{ns}	0.500^{ns}	0.133^{ns}	0.867^{ns}
	7 km h^{-1}	0.677 ^{ns}	0.323 ^{ns}	0.500^{ns}	0.500^{ns}
Total grain losses (kg ha^{-1})	5 km h^{-1}	0.179 ^{ns}	0.821^{ns}	0.289^{ns}	0.711^{ns}
	7 km h^{-1}	0.677 ^{ns}	0.323^{ns}	0.500^{ns}	0.500^{ns}

C - clustering; M - mixture; T - trend; O - oscillation; * non-randomness standard values detected by the probability test, at $p < 0.05$; ^{ns} randomness standard values detected by the probability test, at $p > 0.05$; **grain losses in the reel and due to deficiency in cutting height; *** grain losses in the track and cleaning systems.

Analysis of the control charts revealed that most quality indicators related to harvester performance indicated stability or low instability. The exception was rotor speed at the 5 km h^{-1} travel speed, for which 50% of the values were outside the control limits, indicating total process instability (Figures 1 to 5). This instability resulted from clustering and trend patterns observed in the run charts (Table 2). For water temperature at a travel speed 5 km h^{-1}, engine oil pressure and fuel consumption at a travel speed of 7 km h^{-1} there were no patterns occurring (Table 2). For quality indicators presenting stability, even those indicating patterns, the soybean mechanical harvesting process can be considered to be affected only by natural causes. Higher travel speed also resulted in higher variability of engine rpm, oil pressure and engine water temperature (Figures 1, 2 and 3). For engine rpm (Figure 1), although this variable exhibited higher variability at a travel speed of 7 km h^{-1}, the harvester engine always worked within the rpm range, resulting in higher power and lower fuel consumption per hour, with little influence from external factors that could result in high variation or damage to the machine performance. The same applies to engine oil pressure (Figure 2).

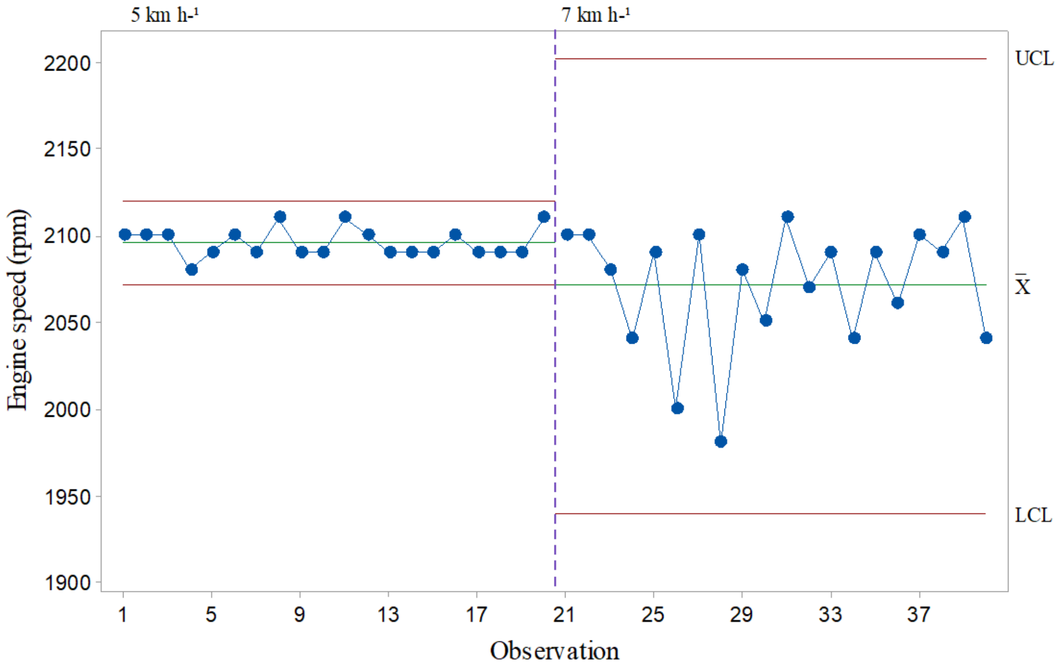

FIGURE 1. Control chart for engine rpm (rpm). UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

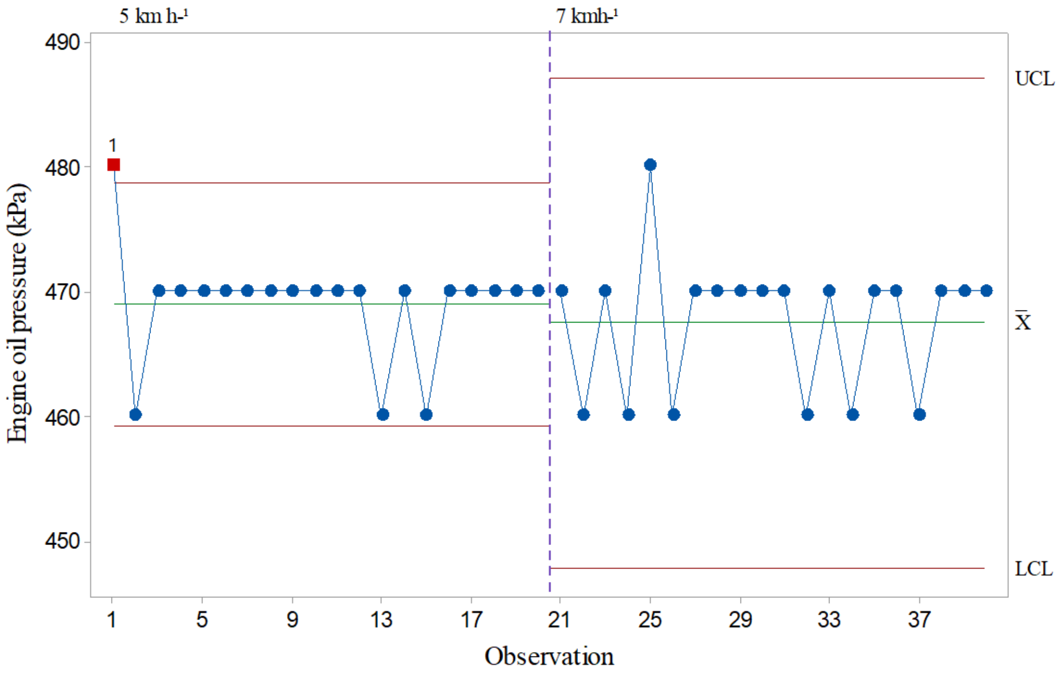

FIGURE 2. Control chart for engine oil pressure (bar). UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

Regarding the engine water temperature (Figure 3), the occurrence of points outside the control limits did not really indicate process instability, as the harvester engine temperature may vary between 82 and 90°C (Voltarelli et al., 2015), and all values within this interval correspond to full functioning of the harvester cooling system.

Of the quality indicators related to harvester performance, only fuel consumption (Figure 4) and rotor speed (Figure 5) exhibited greater distance between limits at a travel speed of 5 km h^{-1}. Fuel consumption (5 km h^{-1}) exhibited instability due to a lower quantity of plant material present in a strip of the evaluated area, demanding lower engine power and resulting in lower fuel consumption. These results are similar to those reported by Mazetto & Lanças (2009) and Chioderoli et al. (2012).

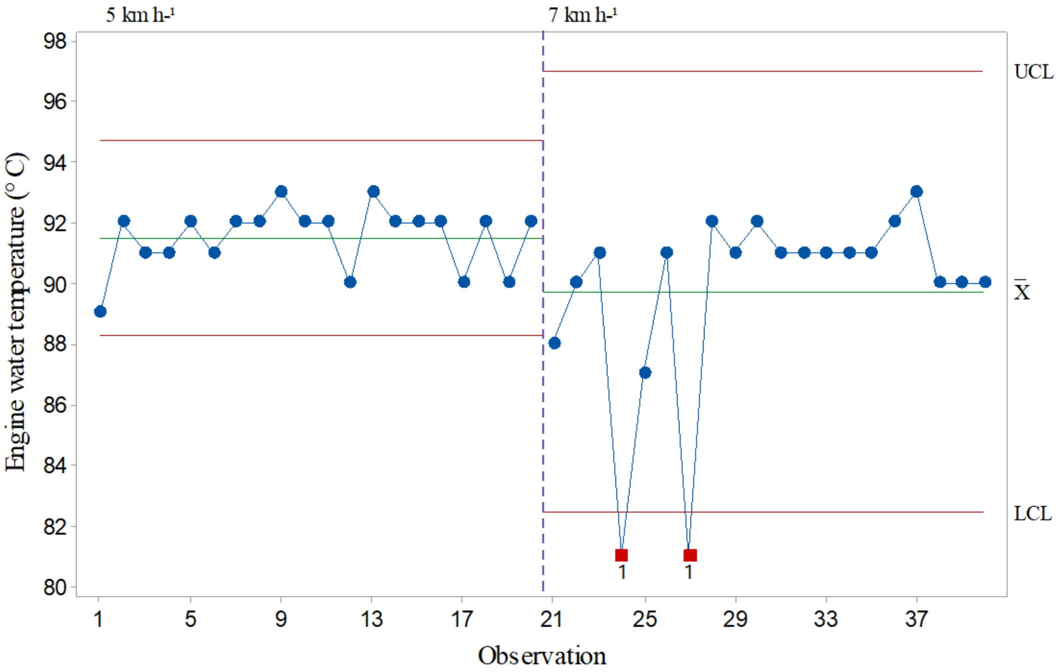

FIGURE 3. Control chart for engine water temperature (°C). UCL: upper control limit. LCL: lower control limit. $\overline{x}$: mean.

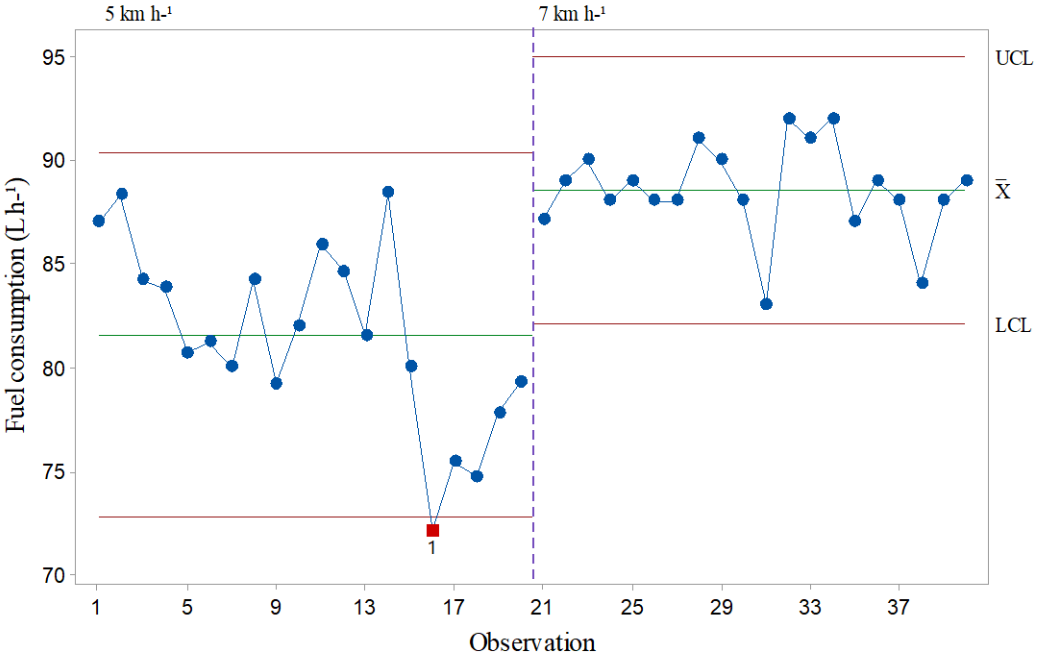

FIGURE 4. Control chart for fuel consumption (L h^{-1}). UCL: upper control limit. LCL: lower control limit. $\overline{x}$: mean.

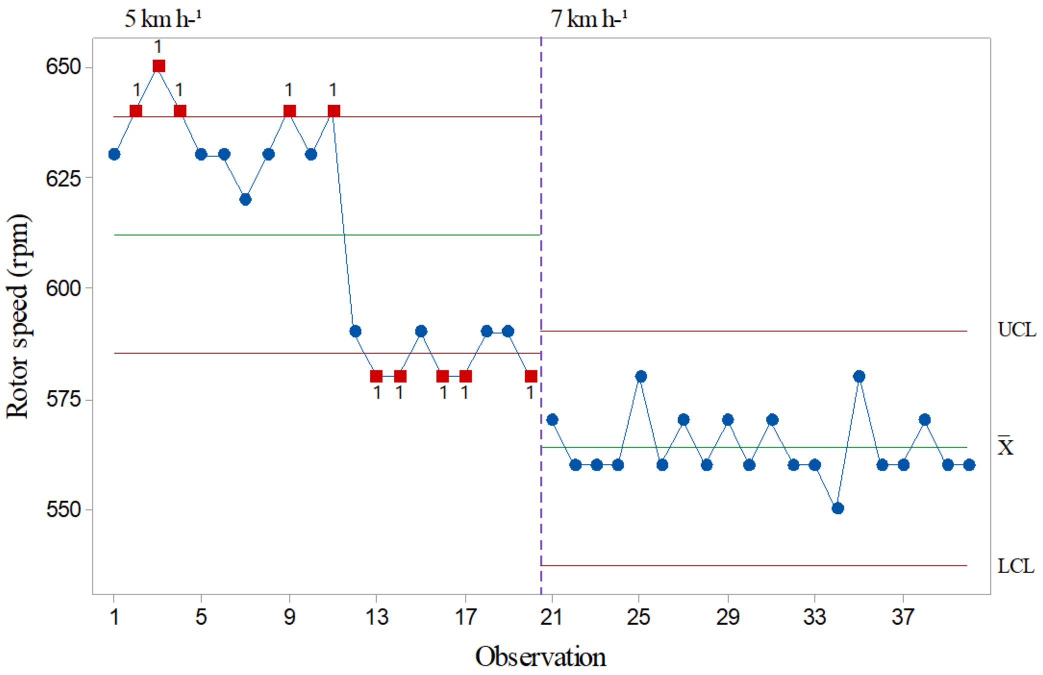

FIGURE 5. Control chart for rotor speed (rpm). UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

Although points were observed to occur outside the control limits, the grain moisture contents were within the ideal range for soybean harvest according to EMBRAPA (2005), i.e., between 12 and 14% (Figure 6). This allows the use of more constant harvester internal mechanism settings, such as the rotor rpm and concave clearance, thereby decreasing losses and mechanical damage.

Regarding cutting height, it was more difficult to maintain a lower cutting height at a travel speed of 7 km h^{-1} (Figure 7), probably owing to the fact that the response time of the cutting height sensor was longer at a higher speed. However, the difference in cutting height at a travel speed of 7 km h^{-1} did not result in higher losses in the reel and due to deficiencies in the cutting height (Figure 8).

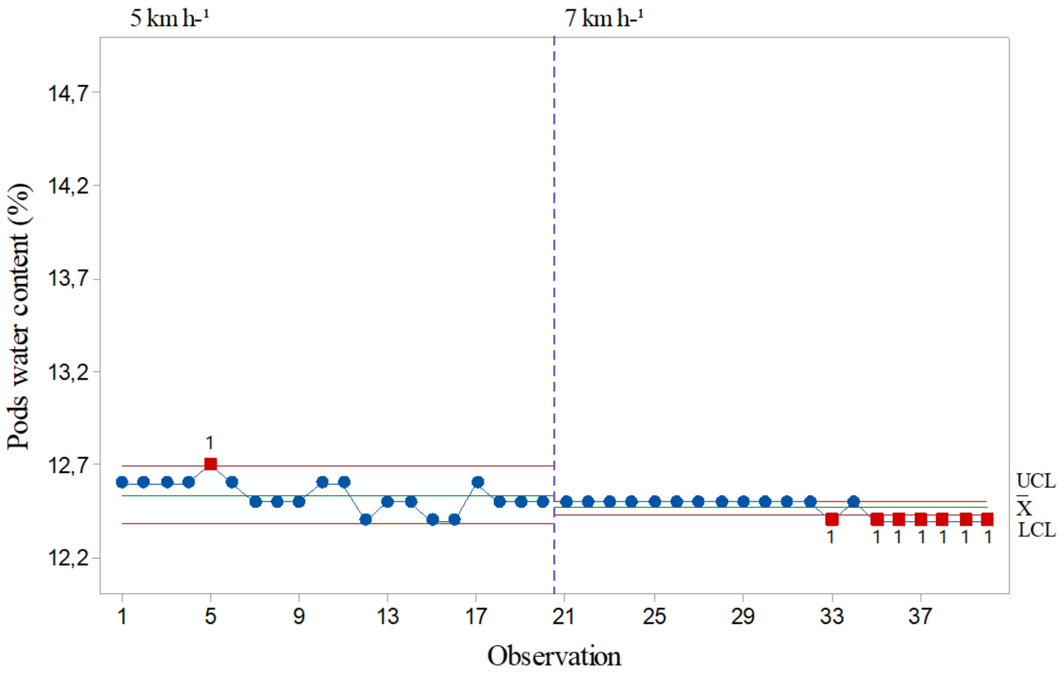

FIGURE 6. Control chart for grain moisture content (%). UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

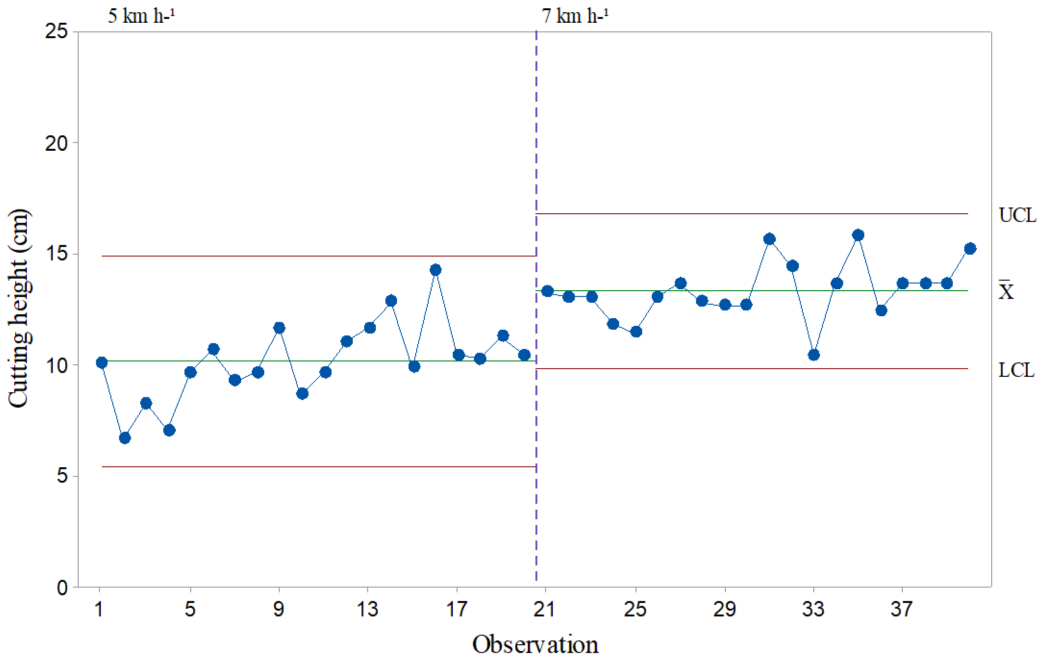

FIGURE 7. Control chart for cutting height (cm). UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

For losses in the track and cleaning systems (7 km h^{-1}), points were observed outside the control limits (Figure 9). These points resulted in higher average losses in the track and cleaning systems, greater total grain losses, and thus higher control limits.

The total grain loss, which was higher at points 10 and 11 (Figure 10), was mostly influenced by losses in the track and cleaning systems, which also resulted in no control of total grain losses.

The high variability observed for grain losses in the track and cleaning systems and total grain losses led to harvesting process instability, indicating the need to monitor this process to improve its quality. This result is in accordance with the results of Toledo et al. (2008).

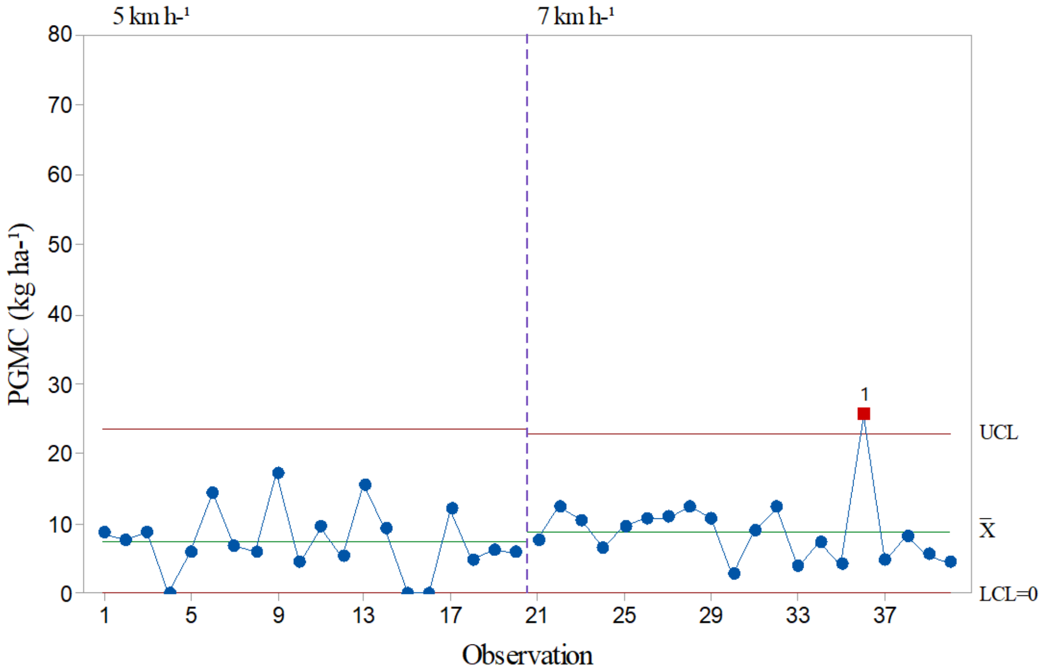

FIGURE 8. Control chart for grain losses in the reel and due to deficiency in cutting height (GLRH) (kg ha^{-1}) after soybean mechanical harvesting. UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

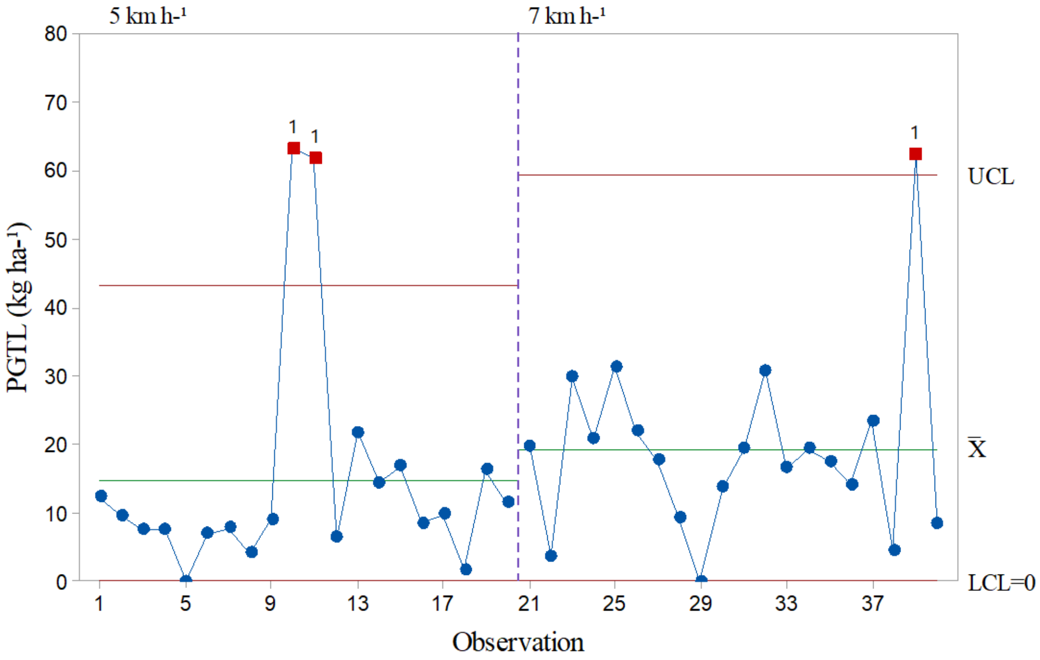

FIGURE 9. Control chart for losses in the track and cleaning systems (GLTC) (kg ha^{-1}) after soybean mechanical harvesting. UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

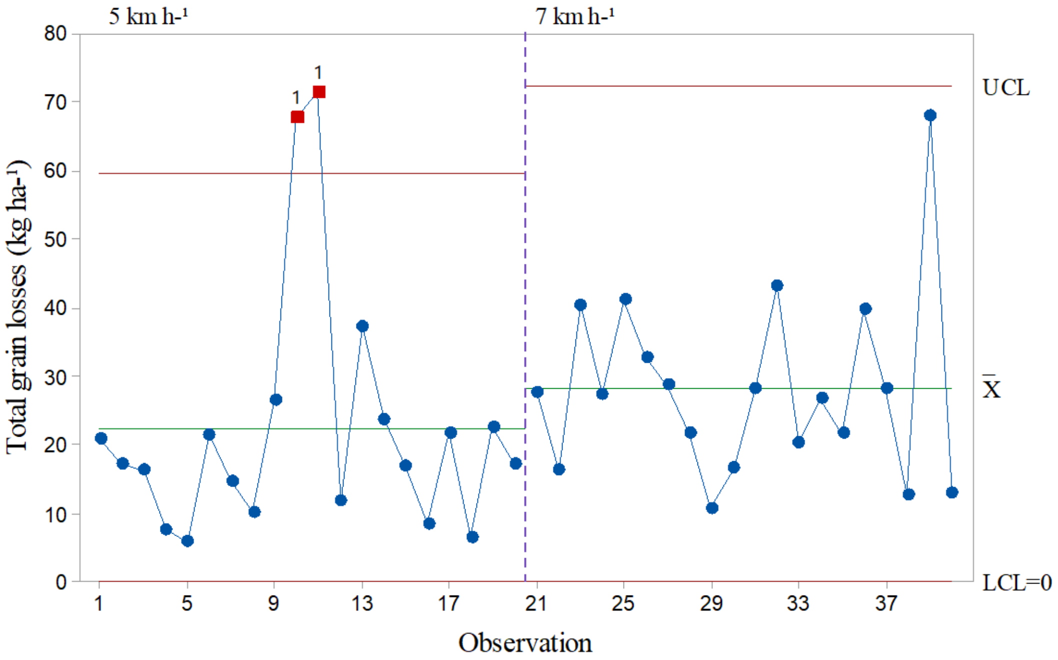

FIGURE 10. Control chart for total losses (kg ha^{-1}) after soybean mechanical harvesting. UCL: upper control limit. LCL: lower control limit. $\bar{x}$: mean.

Process instability was observed for engine oil pressure (Figure 3), fuel consumption (Figure 4), rotor speed (Figure 5) and total grain losses (Figure 6) at 5 km h^{-1}; water temperature (Figure 1) and losses in the track and cleaning systems (Figure 9) at 7 km h^{-1}; and grain moisture content (Figure 10) and losses in the reel and due to deficiencies in the cutting height (Figure 2) at both speeds. However, most of these variables had 5 to 10% of their points outside the control limits, whereas the rotor speed (at 5 km h^{-1}) and grain moisture content (at 7 km h^{-1}) had 50% and 35% of their points outside the control limits, respectively. Considering the high variability usually observed for quality indicators in a harvesting process (Silva et al., 2013b), the quantity of points observed outside the control limits was low and therefore did not indicate real process instability.

CONCLUSIONS

The quality of the soybean harvesting operation was considered stable, owing to the small fraction of points outside the control limits for most indicators evaluated.

Increasing the harvester travel speed from 5 to 7 km h^{-1} resulted in higher average losses in the mechanical harvesting system.

The total grain losses were less than the acceptable levels for soybean for the two travel speeds, but the harvesting process was unstable.

Losses in the track and cleaning systems contributed the most to total grain losses at the two travel speeds.

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