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STATISTICAL PROCESS CONTROL AND GEOSTATISTICS ON THE CHARACTERIZATION OF THE NOISE PRODUCED BY A BACKHOE LOADER

Fabiano Battermarco da Silva[1], Gabriel Araújo e Silva Ferraz[1], João Paulo Barreto e Cunha[2], Diego Bedin Marin[3]*, Lucas Santos Santana[1] & Luana Mendes dos Santos[1]

1 - Federal University of Lavras, Agricultural Engineering Department, Lavras, Brazil

2 - Federal University Rural of Rio de Janeiro, Engineering Department, Rio de Janeiro, Brazil

3 - University of Florence, Department of Agriculture, Food, Environment and Forestry, Via San Bonaventura, Florence, Italy

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ABSTRACT

Workers in their labor activities may be subject to operational risks, such as noise. The objective of this work was to use geostatistics and Statistical Process Control (SPC) through individual charts to map and characterize the magnitude of the spatial variability of noise produced by a backhoe, to identify areas of health for workers. The experiment was developed at the technical college of the Federal Rural University of Rio de Janeiro. A 63-kW backhoe loader and a digital decibel meter were used to collect noise levels at points distributed in a regular 2.0 x 2.0 m sampling grid around the machine. The spatial dependence of the noise was analyzed by adjusting the Wave-type semi-variogram, interpolation by ordinary kriging, and SPC. It was possible to characterize the spatial dependence of noise levels produced by the backhoe as well as to carry out, through individual letters in dialogue with geostatistics, the mapping of their spatial distribution to identify healthy areas for workers. It could have been found in the evaluation of the backhoe loader control chart, that there was no reduction in the variability of noise data, which was approximately 73.29 dB(A) for the sampled points. This shows an average very close to the analysis found in the execution of the descriptive statistics of the noise generated by the backhoe loader.

Palavras-chave:
Conforto acústico
Saúde do trabalhador
Dependência espacial

CONTROLE ESTATÍSTICO DE PROCESSO E GEOESTATÍSTICA NA CARACTERIZAÇÃO DO RUÍDO EMITIDO POR UMA RETROESCAVADORA

RESUMO

Trabalhadores em suas atividades laborais podem estar sujeitos à riscos operacionais, tais como o ruído, que quando expostos excessivamente a este, ficam sujeitos a ocorrencia de danos. A influência deste agente pode ser ainda mais agravada uma vez que este não deixa traços visíveis no ambiente laboral. Objetivou-se utilizar o Controle Estatístico de Processos (CEP) através de cartas individuais e a geoestatística para mapear e caracterizar a magnitude da variabilidade espacial do ruído emitido por uma retroescavadora, visando identificar zonas de salubridade para os trabalhadores. O experimento foi desenvolvido no colégio técnico da Universidade Federal Rural do Rio de Janeiro (CTUR-UFRRJ). Utilizou-se uma retroescavadora com potência de 63 kW e um decibelímetro digital para a coleta dos níveis de ruído em pontos distribuídos numa malha amostral regular de 2,0 x 2,0 m ao redor da máquina. A dependência espacial do ruído foi analisada por meio de ajuste de semivariograma do tipo *Wave*, interpolação por krigagem ordinária e CEP. Foi possível caracterizar a distribuição espacial dos níveis de ruído emitido pela retroescavadora, bem como realizar, através das cartas individuais combinadas à geoestatística, o mapeamento de sua distribuição espacial de forma a identificar zonas salubres aos trabalhadores. Na avaliação da carta individual de controle da retroescavadora, percebe-se que não houve uma redução da variabilidade de dados de ruído, ficando em uma média de 73,29 dB(A) para os pontos amostrados. Isso nos mostra uma média bem próxima com a análise encontrada na realização da estatística descritiva de ruído emitido pela retroescavadora.

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Email (corresponding author)*: db.marin@hotmail.com

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INTRODUCTION

The noise produced by farming machines propagates through space, and as it moves away from the emitting source, its effects decrease. However, it has become important to observe and map how this propagation occurs. Most of the studies carried out to evaluate the noise produced by farming machines only considered its effects on the worker disregarding that the noise produced by these machines propagates, which can also affect the other workers involved in the farming operations.

Therefore, Souza *et al*. (2001) demonstrated that exposition to noise is one of the most common occupational risk factors and that hearing loss is one of the most important effects on the human body. In addition, studies that have been carried out since the 1970s have shown that noise exposure can cause cardiovascular disorders.

To study the effects that noise exposure can generate, it is necessary to understand the concept of noise associated with sound intensity. Sound intensity can be defined as the variation of atmospheric pressure within the limits of the amplitude and frequency range to which the human ear responds (SAPATA, 2010). Noise, on the other hand, is defined by Oliveira Júnior and Cunha (2009) as a combination of sounds that cause feelings of discomfort and are constantly present in people's daily lives.

Nevertheless, the problems that noise could cause were not considered, as machine design has focused on maximizing efficiency at the expense of the human factor. However, it is known today that the operator needs comfort and safety in his or her operating station, and stress can affect the performance and effectiveness of the labor activity, increasing fatigue and discomfort (ALVES *et al*., 2011).

Consequently, a demand has arisen to evaluate and characterize noise in the workplace, and one of the ways is through the use of geostatistics. This essentially includes the modeling of semi-variograms, which will enable the development of interpolation through kriging to obtain contour maps and/or isocores (MACHADO *et al*., 2007).

The use of geostatistics is currently growing and has been applied in several fields of knowledge such as ecology (RATUCHNE, 2010) and climatology (OZTURK & KILIC, 2016), and also for the study of machine noise such as the work of Damasceno *et al*. (2019), Gonçalves *et al*. (2019) and Ferraz *et al*. (2013).

In addition to the spatial analysis of noise, it is also important to know the quality of the process. Therefore, the use of statistical process control (SPC) becomes interesting. According to Alencar (2004), the SPC is a set of online quality monitoring tools capable of providing a thorough description of the behavior of the process, identifying its variability, and enabling its control over time. For this, continuous analysis of the data is carried out and the likely special causes that cause instabilities in the process under study are blocked.

The purpose of using SPC is to improve production processes by reducing their variability and, consequently, improving quality levels in the results. It is normal for factories to not optimize processes, in the sense that they are characterized by high levels of efficiency, however, there are tools within the SPC for monitoring and, consequently, improving the process (CARVALHO & PALADINI, 2005).

According to Lima *et al*. (2006) the efficient use of SPC is based on the assumption that: if the conditions of a process are methodically maintained, it will be subject only to the effects of Common Causes, configuring itself by a Normal Distribution. Thus, as it is a known process, its occurrence can be predicted.

According to Yazigi (2013), a backhoe loader is a machine designed to dig, level, and plan the terrains in addition to consisting of a hydraulic system, transmission system, electrical system, a shovel mounted in front of the vehicle, brakes, axles, and clutches, being used in rural and urban buildings.

Studies evaluating farming tractors with more than 50 kW (68 hp), found that the protection cabin reduces the noise level in the operator's ears, and, therefore, it could have been inferred that the cabin is a relevant factor in the acoustic insulation at the workplace of operators (SOUZA & LEVITICUS, 1995).

It can be observed that there are no studies involving the SPC as well as the geostatistical analyses regarding the civil machine studied in dialogue with the maps of insalubrity.

Given the above, the objective of this work was to use Statistical Process Control (SPC) through individual charts and geostatistics to map and characterize the magnitude of the spatial variability of the noise produced by a backhoe loader, to identify health zones for workers.

MATERIAL AND METHODS

For the experiment, an open field located at the technical college of the Federal Rural University of Rio de Janeiro (CTUR-UFRRJ), Seropédica, Rio de Janeiro, Brazil was selected.

A JCB 3C backhoe loader was used with a nominal power of 63 kW (86 hp) and protective glass on the front of the cabin, with the sides and rear open. Also, the civil machine was manufactured in 2012.

The noise level of this backhoe loader was determined according to the methodology described in NBR-9999 (ABNT, 1987a) in which the room temperature ranged from -5°C to 30°C and the air velocity was less than 5.0 m.s^{-1}.

Regarding noise measurement, a digital decibel meter model DEC-460 was used for noise level emission measurements, whose description is based on a sound pressure level measurement instrument with instantaneous reading and peak reading, automatic scale, and frequency weighting in A and C. Regarding the measurement scale, there is a measurement from 35 to 130 dB(A) and an internal calibrator.

Measurements were performed on a sample grid following the methodologies proposed by the works of Gomes *et al.* (2021), Gonçalves *et al.* (2019), Santos *et a*l. (2020). Hence, a meter-arbitrated spatial coordinate was established, whose operator seat corresponds to the central point (0.0) and the sample grid with 121 points was evenly distributed every 2 m x 2 m (Figure 1). Noise measurements were performed at the average height of the operator's ear (1.70 m).

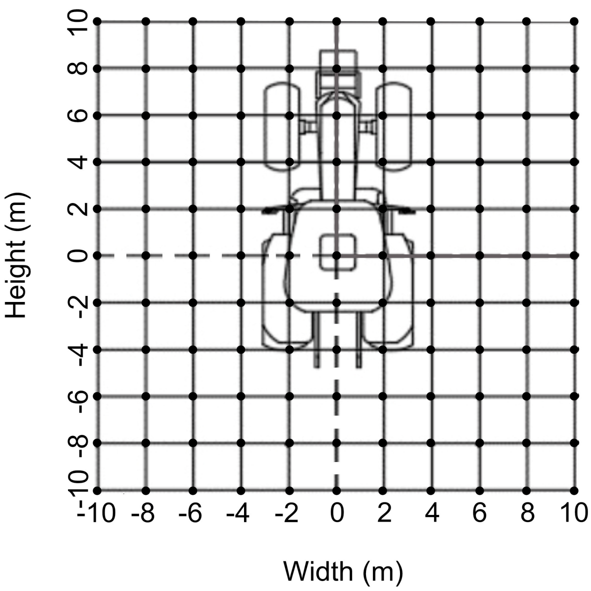

Figure 1. Sample grid of the levels of noise produced by the backhoe. The dark dots are the sample points

The spatial dependence of the noise produced by the backhoe during the operations was analyzed utilizing classical semi-variogram adjustment using the Ordinary Least Squares (OLS) method and the Wave model. The classic semi-variogram was estimated according to equation 1:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad (1)$$

where N (h) is the number of experimental pairs of observations $Z(x_i)$ and $Z\ (x_i+h)$ separated by an h distance. The semi-variogram is represented by the graph $\gamma(h)$ versus h. Consequently, from the adjustment of a mathematical model to the calculated values of γ(h), the coefficients of the theoretical model are estimated for the semi-variogram denominated nugget effect, C_0; plateau, C_0+C_1; and the range, a (VIEIRA *et al*., 1983).

The theoretical model adjusted to the experimental semi variogram was the Wave model (GONÇALVES *et al*., 2019), given by equation 2:

$$\gamma(h,\beta) = C_1^2 + \frac{a}{h}\ sen \left(\frac{h}{a}\right)^4 \qquad (2)$$

where C_1 is the contribution, *a* is the range and *h* is the distance between the observed points.

According to Andrioti (2004), Equation (2) presents periodic variations, which is an indication of a non-monotonic growth of semi-variance with distance and shows models with and without a plateau. According to Carvalho *et al*. (2004), these non-monotonic structures may have reduced wave amplitudes, both isotropic and anisotropic. Another analysis that must be done is based on the relationship between theoretical and practical scope. Chilès and Delfiner (1999) state that the practical range is reached by the Wave model when h is approximately equal to 4.5a.

The statistical computational system R and its geoR package (RIBEIRO JÚNIIOR & DIGGLE, 2001) were used to perform the geostatistical analysis. The software QGIS 7.2.2, which is free of charge, was used to plot the maps.

The results found in this work were compared with the tolerance threshold of the noise exposure which is established by Annex 1 of NR 15 (BRASIL, 2019).

In addition to the geostatistical analyses, the data of the noise produced by this backhoe loader were evaluated through the SPC using the individual control charts, which are graphs used to monitor a process, in which a more detailed description of its behavior is obtained, identifying its variability and allowing its temporal control. For the composition of the individual charts in the SPC, the Minitab 19 software was used. It was separated into five consecutive stages. Such stages were formed to facilitate the analysis of the data obtained in the sampling grid. From these data, stage 1 was developed from a 0-2 m radius, stage 2 was created from a 2-4 m radius, stage 3 was built from a 4-6 m radius, stage 4 was made from a 6-8 m radius and stage 5 was composed of an 8-10 m radius.

RESULTS AND DISCUSSION

Based on the descriptive statistics of the noise produced by the backhoe loader, the minimum and maximum values, the coefficient of variation, and also the noise average were obtained (Table 1). It could have been observed the variation in the data; however, using this analysis did now enable a state where the highest or lowest values of noise produced by the machine occur, therefore geostatistical studies are required.

The results of the geostatistical analysis of the noise levels produced by the backhoe loader in operation can be observed in Table 2. Thus, it can be seen that the semi-variogram (Figure 2) and its parameters (nugget effect, “C_0”; contribution, “C_1”; threshold, “C_0+C_1”; and range, “a”) were obtained using the Ordinary Least Squares method and the Wave model (Figure 2).

The analysis of Figure 2 and Table 2 showed that the practical range (a`) of the spatial distribution of the noise produced by this machine was 7.54 m, which means that up to this observed distance, the variable under study suffers the influence of its position in space.

Table 1. Descriptive statistics of the noise produced by the backhoe on February 7th, 2014 from 9:00 a.m. to 10:20 a.m.

Min	Max	X	Md	SD	Var	CV	K	Asymmetry
67.70	96.00	75.54	75.00	5.01	25.11	6.63	1.72	1.02

Min – Minimum value of the variable; Max – Maximum value of the variable; x - Mean; Md – Median; DP – Standard deviation; Var – Variance; CV – Coefficient of variation; K – Coefficient of kurtosis

Table 2. Estimated parameter of the experimental semi-variogram for the level of noise produced by a backhoe

Tractor	C_0	C_1	C_0+C_1	a	a`	ME	SD_{ME}	RE	S_{RE}
Backhoe	0.7866	28.0451	28.831	2.5223	7.5455	-0.033	1.9189	-0.01454	1.9757

C_0 – Nugget effect; C_1 – Contribution; C_0+C_1 – Plateau; a – range; a` – practical range; ME – mean Error; SD_{ME} – Standard deviation of the Mean Error; ER – Reduced Mean Error; S_{RE} – Standard Deviation of the Reduced Errors

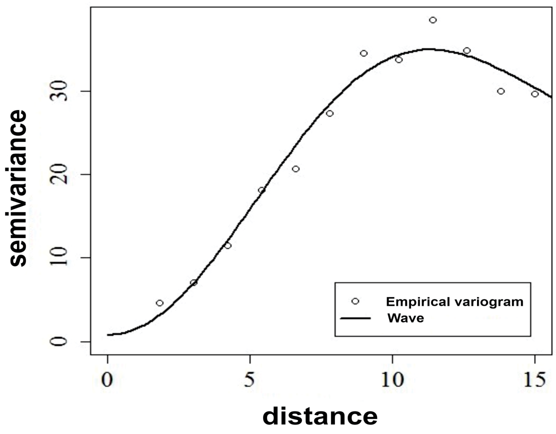

Figure 2. Semi variogram of the noise produced by the backhoe

It can be seen in Figure 3 that the further from the tractor, the more bluish the spots, signaling a decrease in the noise level, making it more adequate for the workers and not requiring the mandatory use of PPE as the noise levels are less than 85 dB(A). The minimum noise value produced by this tractor was 62.8 dB(A) (Table 2) observed at point (-8, 20) (Figure 3), that is, the furthest from the producing source.

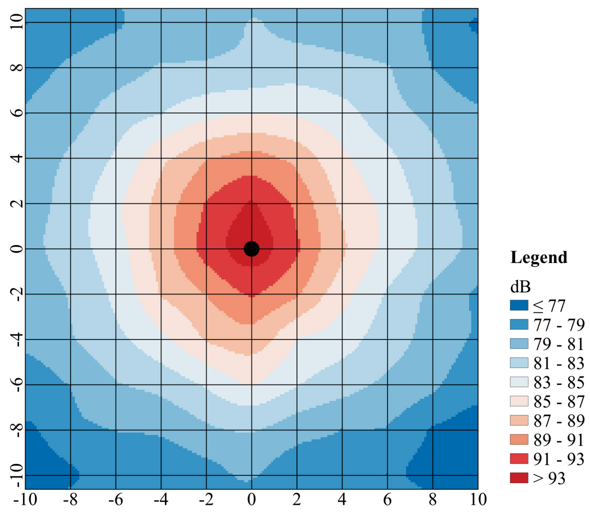

Figure 3. Spatial distribution map of the noise produced by the backhoe

It is also observed in Figure 3 that within a 6-m radius from the machine, the highest noise levels were found, indicated on the map by the red color. As the noise levels within this radius are above the legislation and exceed the standard limits, there is an unhealthy situation for the operator and the worker of the operation. In this situation, according to NR 15, there is a need to adopt preventive methods such as the use of Personal Protective Equipment (PPE) to prevent the aforementioned damages.

According to NBR 10152 (ABNT, 1987b), when a person is subjected to high levels of noise, the body is affected, which may reflect in physiological, biochemical, cardiovascular aspects, and also in the individual's psychological behavior. These aspects include a rise in blood pressure, heart rate, insomnia, fatigue, decrease in productivity, anxiety, among others (SILVA *et al.*, 2012).

In the legal concept, the work-related accident results in the occurrence of injury to the body or health when the worker is performing his or her work, not only at the place but also throughout the journey. Therefore, in the event of an accident, the worker is entitled to financial compensation while unable to work or compensation in the event of permanent damage (OLIVEIRA, 2013).

The farm worker must be aware of the ergonomic principles that seek his or her best adaptation concerning the working conditions about psychophysiological characteristics. Therefore, there are regulatory standards, such as NR 31 (BRASIL, 2018), which establishes the precepts to be observed in the work environment, to make the establishment and execution of activities such as farming a safe, healthy work environment.

Works carried out by Baesso *et al.* (2015) showed that average noise values for tractors that had original factory closed cabins presented acceptable noise levels near the operator's ear for a workload of 8 hours of work per day, stipulated by NR 15 (BRASIL, 2019).

The maximum value of the noise emission found in the assessed backhoe was 94.0 dB(A), in the operator's seat (Figure 4), thus, there is a maximum allowed daily exposure of 2 hours and 15 minutes according to NR 15 (BRAZIL, 2019).

The values of the noise produced by the backhoe loader that are within the daily exposure limit of 8 hours, that is, noise up to 85 dB(A), were observed within a 6-m radius (Figure 4).

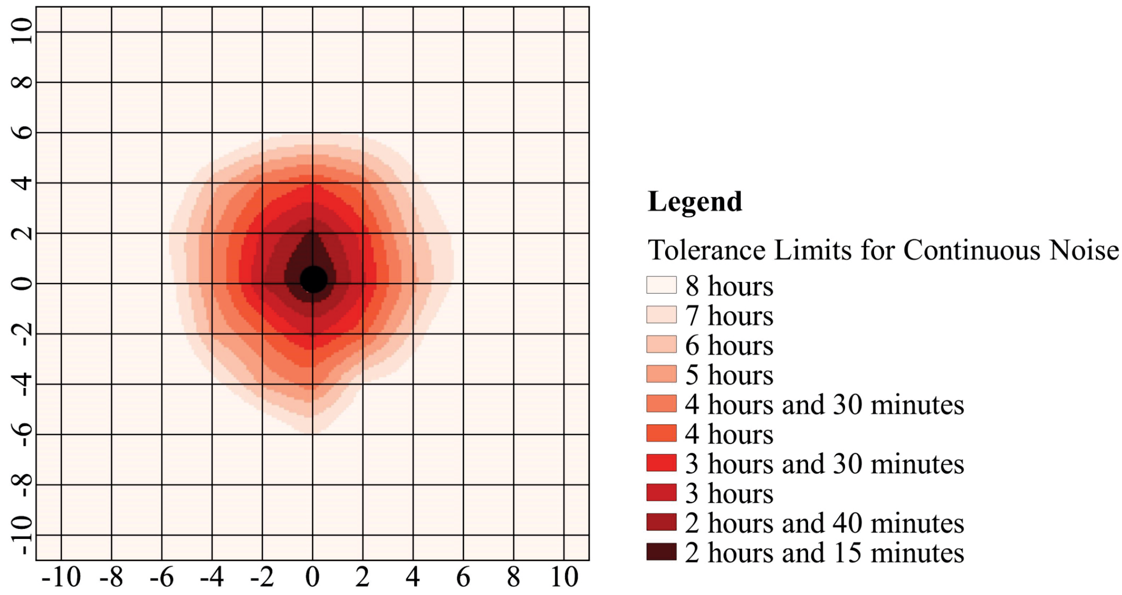

Figure 4. Spatial distribution map of the period of exposition to the noise produced by the assessed tractor

Thus, it is observed that the backhoe operator and any possible assistant will be subject to the harmful effects of the noise produced within this radius, therefore, the use of ear protectors is recommended during the operation (Figure 5).

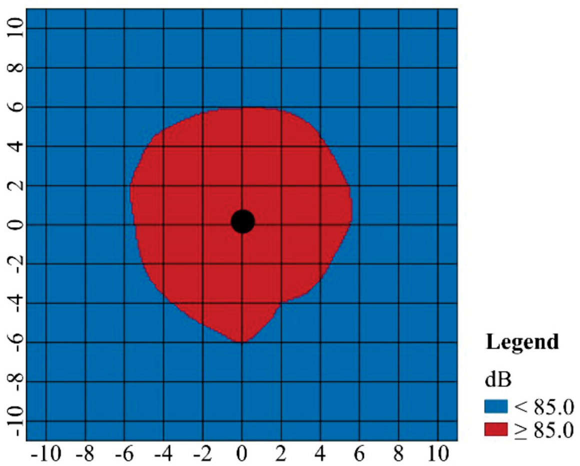

Figure 5. Map of the need for the use of Personal Protective Equipment (PPE)

It should be observed through the SPC analysis using individual control charts that a point beyond the limits is not the only way to detect if a process is out of control; there are at least ten other sensitization rules for Shewhart's control charts. Some of these rules were proposed by Follmer (2013), among them, the one point beyond the control limits, which is one of the most used rules; and the others that can be included within the non-randomness item, such as the rule of two or three consecutive points beyond the limits of two sigmas or a sequence of eight consecutive points on the same side of the central row.

According to Silva (2003), the random error or repeatability increases the dispersion of measurements. When the error acts from the beginning, this effect produces a departure from the control limits. Therefore, the noise chart of a stable process, contaminated with pure random errors, will present the same false alarm probability as a hypothetical chart constructed with the values of the measurand. This fact can be seen in Figure 6, where it is also highlighted that the measurements are also contaminated by repeatability.

Furthermore, according to Silva (2003), the systematic error which is linearly dependent on the value of the measurand, when it presents zero value in the average of the process, does not distort the perception of the average but modifies the dispersion of points in the chart and, consequently, the control limits. Also, according to the author, if the error has a positive angular coefficient, this will cause an increase in the dispersion of the measured values in relation to the dispersion of the measured values. If the slope is negative, the effect is inverse.

Also, the analysis of Figure 6 showed that the average was 72.22 dB(A) for the sampled points.

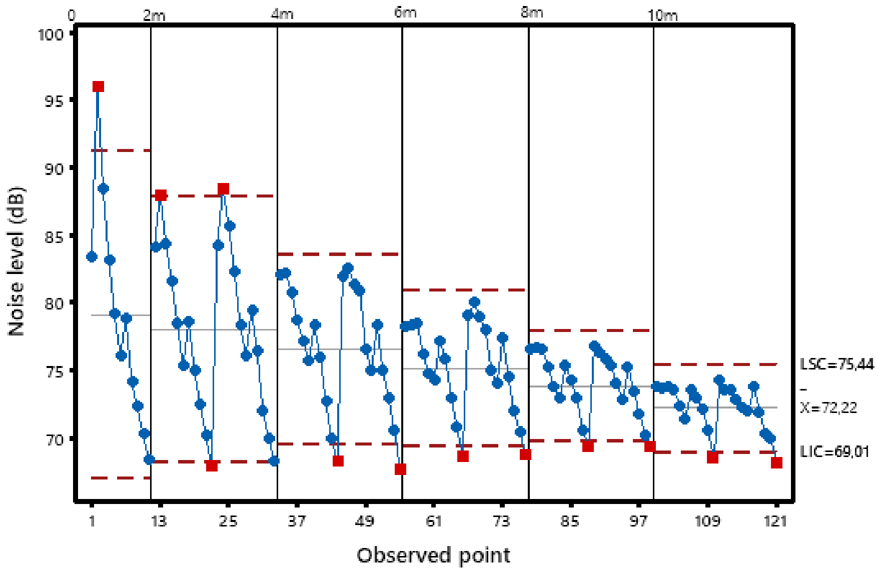

Figure 6. Control chart for the noise levels of the backhoe

This shows us a very close average with the descriptive analysis found in Table 1. However, it can be seen that, in stage 1, there was a variation concerning this average. This phenomenon occurred due to the proximity of the mentioned stage to the producing source.

Out of the total of five subgroups, which ranged from 72.22 dB(A) to 79.13 dB(A), two are beyond the desired criteria during the operation. Even so, the process is out of statistical control, which means that there are external (special) causes interfering with the process. When observing the points that are outside these limits, it can be seen that these data were generated by incorrect data collection procedures or the manufacturing year of the machine may have interfered with these values (c, 2017).

Finally, the use of maps such as the one in Figures 4, 5 extracted from Figure 3 as well as Figure 6, based on the values recommended by NR 15 (BRASIL, 2019), is of fundamental importance for the management of acoustic healthiness during use of the civil machine, as they facilitate the understanding of the risks caused by exposure to noise.

CONCLUSION

- The results of this study enabled the characterization of the magnitude of the spatial variability of noise data produced by a backhoe loader. It was also possible to map the noise produced by this machine as the data presented a spatial dependence structure.
- The Wave model was adjusted to the variables studied for the assessed civil machine, and the use of geostatistics allowed adjustment points with different spatial variability in this machine.
- The process has been thoroughly studied. Special causes were also identified according to process variations.
- The use of the maps obtained in this work allowed the definition of adequate operational management zones for the protection of workers. In addition, they allowed the development of healthy work plans, indicating the use of the most appropriate personal protective equipment (PPE) for the operation of the backhoe loader.
- The observation of the maps enabled the definition of adequate operational management zones for the protection of workers, therefore, allowing the development of healthy work plans, indicating the use of the most appropriate personal protective equipment (PPE) for the operation of the backhoe loader.

AUTHORSHIP CONTRIBUTION STATEMENT

SILVA, F.B.: Conceptualization, Data curation, Methodology, Project administration, Writing – original draft; **FERRAZ, G.A.S.:** Conceptualization, Data curation, Project administration, Supervision, Writing – review & editing; **CUNHA, J.P.B.:** Data curation, Formal Analysis, Investigation, Validation, Writing – review & editing; **MARIN, D.B.:** Formal Analysis, Resources, Software, Visualization, Writing – review & editing; **SANTANA, L.S.:** Conceptualization, Data curation, Formal Analysis, Methodology, Writing – review & editing; **SANTOS, L.M.:** Conceptualization, Data curation, Formal Analysis, Methodology, Writing – review & editing.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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