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RESEARCH ARTICLE

SHEWHART CONTROL CHARTS FOR MONITORING AN AUTOMOTIVE GLASS FIXING PROCESS

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ABSTRACT

The purpose of this paper is to present parameters of Shewhart control charts to monitor the mean and variability of an automotive industry process. The process consists of preparing and applying polyurethane glue for attaching glass of a panoramic roof to a vehicle. The amount of glue applied must follow the height and length standard specified by Engineering. These are the two quality characteristics considered critical regarding quality and safety for customer. Limits of control plot to monitor the mean and sample amplitude are estimated with 50 size 6 samples, following the principle of rational subgroups. Graphs constructed serve to monitor the quality characteristics of process, and it is possible to evaluate wheather there are special causes that alter the average and/or the variability of process.

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INTRODUCTION

In the early 1930s, quality control emerged in the United States in an industrial application of the control chart compiled by Walter Andrew Shewhart, an employee of Bell Telephone Laboratories. Shewhart (1925) proposed the use of control chart emphasizing the study and prevention of problems related to quality. During World War II (1939-1945), thanks to quality control, a large number of American industries are able to produce military articles of good quality and with low costs. This success is related to the implementation of statistical techniques associated with quality control. The American War Standards Z1.1, Z1.2 and Z1.3 (known as Z-pamphlets), published in 1941 and 1942, consolidate the statistical procedures used during the time of the war, with such repercussions as to be translated and used by several industries of diverse nations of the world (http://www.tandfonline.com/doi/abs/10.1080/00031305.1967.10481808). In the 1950s, Japan widely used quality control by means of activities adaptation based on the American and English systems, creating the Total Quality Control (TQC) in the Japanese style. The TQC is an administrative model created by a group of quality control researchers from the Union of Japanese Scientists and Engineers (JUSE) and is based on many elements, one of them is statistical process control (Campos, 2004).

The speed of information and the new technologies have established a globalized environment of high competition in which price, term, quality and flexibility need to be answered. Controlling variables involved in production process in order to make it more efficient is one of the growing concerns of entrepreneurs. Many systems used in companies need processes of monitoring and production control (Jacobi *et al*., 2002). Controlling processes is the essence of managing a business. Campos (3) defines a process as "a set of causes that provoke one or more effects". These causes are called manufacturing or service factors that can be: raw materials, machinery, measures, environment, labor and method. The use of control charts, unlike after-production inspection, enables quality control during manufacturing, ie, control charts exhibit a focus on defect detection and immediate corrective action if any failure is detected. In this way, by preventing the exit of imperfect products, it can be considered as a preventive method (Deming, 1990). Industry needs to control different process parameters and product data. In industry 4.0, these data and those obtained by means of new technologies will be the basis for all analysis and control systems that will present information that allows decision making. In both industry 4.0 and our current industry, making data-driven decisions based on statistical techniques adds quality to manufacturing processes. The use of Statistical Process Control in a systematized and integrated way is the first step to be in line with industry 4.0 (Reis, 2017). This paper presents a practical contribution on application of control charts in processes.

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The purpose of this research is to present the parameters of control charts to monitor the mean and variability of an automotive industry process. The process consists of preparing and applying polyurethane glue to attach a glass to the panoramic roof of a vehicle. The glue applied must follow the height and length standard specified by Engineering. These are the critical variables that should be monitored. For the construction of control charts, the methods proposed by Costa (2005) and Sampaio (2014) are used. The glass is fixed on panoramic roofs of vehicles produced at a company in the southern region of Rio de Janeiro, Brazil. The company name and the vehicle type are omitted for reasons of secrecy. However, this omission does not compromise the quality and results of the research. The article is structured in five more sections. Section 2 presents the theoretical review of control charts to monitor the mean and variability of a process. A brief description of the panoramic roof installation process is presented in section 3. Section 4 presents results of survey with the construction of control charts and section 5 presents the final considerations and suggestions for future research.

Control Graphs For Medium And Sample Amplitude: Every process must be continuously monitored in order to detect the presence of special causes that increase dispersion and/or take average of the target value. Once the presence of a special cause is detected, an investigation must be conducted to eliminate the special cause. $\overline{X}$ and R control charts are the main tools to monitor processes and signal the presence of special causes. The control chart of $\overline{X}$ for independent data is used to monitor the average (μ) of a process whose quality of interest characteristic X is a measurable quantity represented by the Shewhart model:

$$X_k = \mu + e_k, \quad k = 1,2,.... \tag{1}$$

where e_k é uma variável aleatória IID ~N $\left(0,\sigma_e^2\right)$.

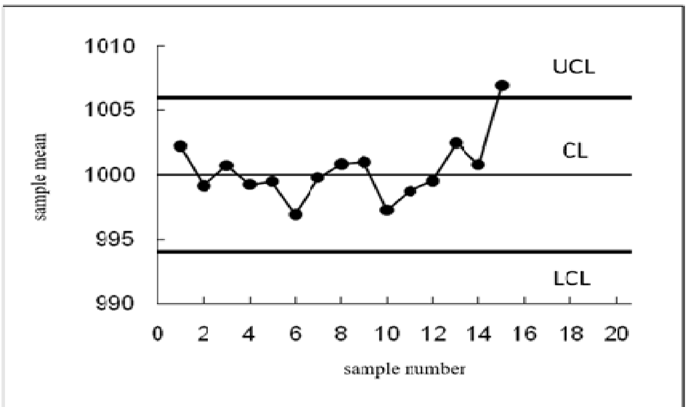
At each time interval h, a sample of size n is withdrawn from the process and the statistic is calculated. The values of the calculated statistic are drawn in a graph that has two limits: lower (*LCL*) and upper (*UCL*) positioned at L standard deviations of the mean. Usually L takes the value equal to 3; in a standard normal distribution this value causes that, in a process exempted from special causes, 99.73% of the observations fall within the limits of control. If points of the calculated statistic, after being marked on the graph, are distributed randomly around the midline (LM), estimated from the overall mean of a significant number of observations, and within the control limits, there is no need to intervene in the process. The mean line and the limits of the graph are established with the process in control:

$$LSC = \hat{\mu}_0 + L\frac{\hat{\sigma}_0}{\sqrt{n}} \tag{2}$$

$$LM = \hat{\mu}_0 \tag{3}$$

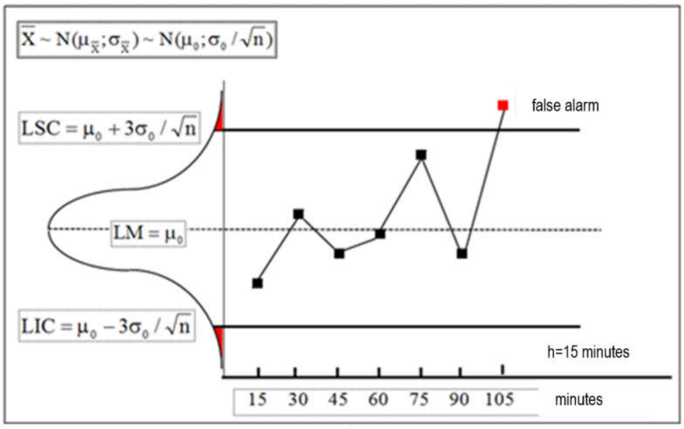
$$LIC = \hat{\mu}_0 - L\frac{\hat{\sigma}_0}{\sqrt{n}} \tag{4}$$

where $\hat{\mu}_0$ estimate of mean of process in control and $\hat{\sigma}_0$ the standard deviation of process under control, L is the opening factor of the control limits and n is the sample size. The graph of $\overline{X}$ is illustrated in Figure 1.When a point appears in the chart region of action (above LSC or below LIC), there is probably some special cause interfering with the process average and should be investigated and corrected. In Figure 1, the sample points behave randomly up to the 14th sample. In the 15th sample, there is a value of $\overline{X}$ in the region above the LSC, region of action, indicating process out of statistical control. The control graph is similar to the test of the following hypotheses: H0 = process under control, H1 = control process. If the graph is $\overline{X}$,so: H_0: $\mu=\mu_0$ and H_1: $\mu\neq\mu_0$. The statistical errors are: error type I (error α)which is the probability of a point falling beyond the control limits, signaling a non-existent special cause, and error type II (error β) is the probability of a point falling within the control limits not signaling a special cause (Leoni, 2012). With the process exempted from special causes, the ideal is that all points of $\overline{X}$ lie within the control limits. However, there is a risk α that a point appears in the plot region of the graph, generating an alarm; in this case, a false alarm. The occurrence of a false alarm is illustrated in Figure 2. Figure 3 illustrates the inertia of the graph in signaling a special cause that changes the average of the process, that is, $\mu\neq\mu_0$.



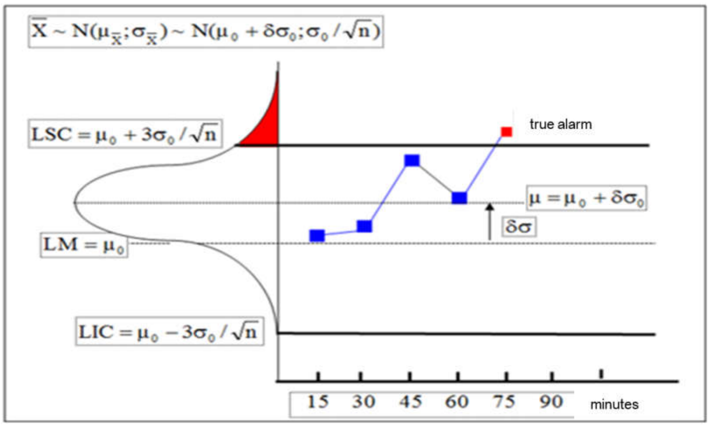
Source: Adapted from Costa (7).

Figure 1. Control chart for the samplemean



Source: Adapted from Costa (7)

Figure 2. Chart of $\overline{X}$ – occurrence of a false alarm



Source: Adapted from Costa (7)

Figure 3. Chart of $\overline{X}$ – occurrence of a true alarm

The signal only occurs when the 5th point, corresponding to the mean $\overline{X}$ of the 5th sample, falls in the region of action of the graph. The sample amplitude control graph is widely used to monitor the variability of a process. The control limits are adjusted in relation to the average line of the graph, ie:

$$UCL_R = \mu_R + k\sigma_R \quad (5)$$

$$LM_R = \mu_R \quad (6)$$

$$LCL_R = \max\{0; \mu_R - k\sigma_R\} \quad (7)$$

being: k the opening factor of control limits; $\mu_R = d_2\sigma_0$ and $\sigma_R = d_3\sigma_0$ the mean and the standard deviation of sample amplitude distribution. Values of d_2 and d_3 are dependent only on the size of the sample n and σ_0 is the standard deviation of the process under control. Tippett (1925), Mahoney (1998) and Kao (2007) present how to calculate the constants$d_2(n)$ and$d_3(n)$ when the quality characteristic has distribution normal and not normal. This article uses the approach presented by Sampaio (2014) for the construction of GC R. The technique consists of using control limits considering a predetermined value for risk α (falsealarm). The authors consider the sample distribution of the relative amplitude (w). For example, by setting the value of□=0.01, we calculate the probabilities P($W < w_{inf}$)= 0.005 and P($W > w_{sup}$)= 0.005. Equations (5) and (7), become:

$$UCL_R = w_{sup}\hat{\sigma}_0 \quad (8)$$

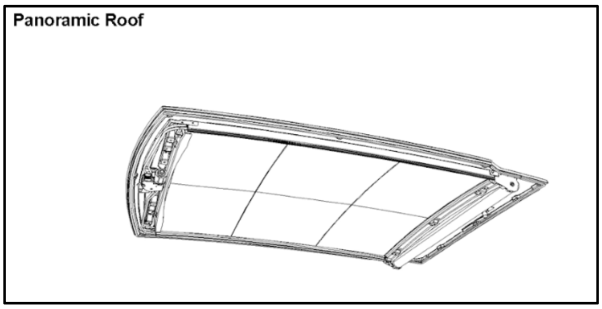
$$LCL_R = w_{\inf}\hat{\sigma}_0 \quad (9)$$

Two advantages are verified with this approach: the result of (9) cannot be negative, allowing detecting improvement in the process, that is, if there is reduction of variability. The second advantage relates to the use of k=3-sigmainthis traditional approach leads to values smaller than the LIC_R calculated in (9), that is, the risk α is greater in the traditional approach. Two phases are considered in the construction of a control chart: a data construction and adjustment phase (phase 1) and a process monitoring and control phase (phase 2). In phase 1, the parameters of the control charts are estimated and in stage 2, the monitoring itself, ie, samples are controlled over time to identify special causes that are active in the process.

Panoramic Ceiling Installation Process: The process of installing a panoramic roof in automotive vehicles consists of the preparation of a glass and application of a polyurethane glue (PU). The glass to be attached to the vehicle roof (see Figure 5) receives a polyurethane glue applied by a pre-parameterized robot with the specifications of the amount of glue and then the glass is glued to the vehicle roof.

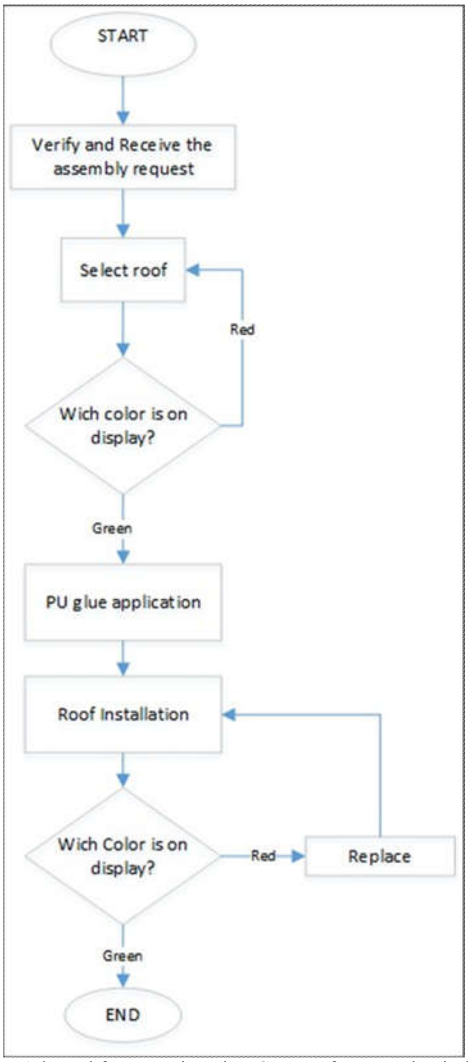
The panoramic ceiling installation process is shown in Figure 4. The sequential steps are: Receipt and verification of assembly order: the operator has in his workstation a bay where daily the glasses are brought from the stock and placed sequentially by identification number in the production order. A wireless code reader is used to verify the identification number of the panoramic roof glass that will be mounted on the workstation.

- **Ceiling selection:** the operator scans the ceiling code. If the light that appears on the code identifier is green, it means that it is the correct glass for mounting on the car and it can proceed to the next step, if it is red, he searches for the correct glass.
- **Application of the PU glue:** the operator picks up the glass with a vacuum manipulator and places it on the table for the robot to apply the polyurethane glue.
- **Ceiling installation:** the operator removes the glass from the application table with the manipulator and positions it on the vehicle roof. There are sensors that assist in the correct positioning of the glass. If a green light is triggered, installation can be completed. If the red light comes on, the glass should be repositioned.



Source: Engineering Center of automotive industry

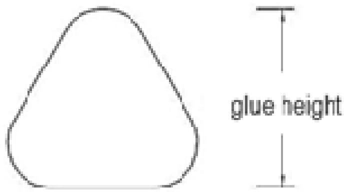
Figure 4. Illustrative image of panoramic ceiling



Source: Adapted from Engineering Center of automotive industry.

Figure 5. Process flowchart

In this process, two quality characteristics are considered critical regarding quality and safety for the customer: the height and length of the glue (Figures 6 and 7). This process must be controlled because if the excess glue exceeds the application margins, it becomes visible to the customer. The amount of glue below the specified allows water, wind or dust to enter through cracks created at the points of deficiency of the material, interfering with the safety of the customer. The limits for specifying the height of the glue are: lower limit of specification = 10 cm and upper limit of specification = 14 cm. The limits of specification of the length of the glue are: lower limit of specification = 6 cm and upper limit of specification = 10 cm. These limits can be used to calculate the process capability and thus evaluate how well the process can meet the specifications. The application process of glue carried out by the robot should, in theory, be repeated equally in all applications. However, because of infinite external factors, equipment maintenance, temperature and humidity, product dilation, PU supplier exchange, can act in the process, causing the length and height values of the glue to be modified. There is a panoramic roof available for testing to evaluate the performance of the robot in relation to the glue application. Daily, a trained operator collects a sample of the height and length of the glue at 6 points (F1 to F6) of the panoramic ceiling (Figure 8).

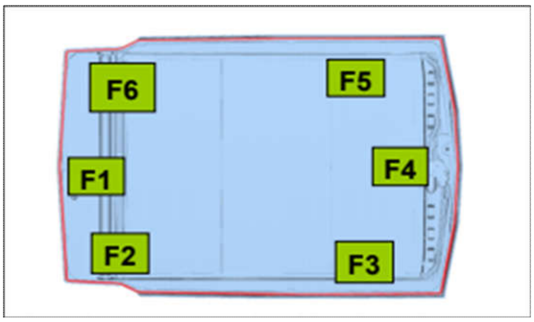


Source:The authors.

Figure 6. Front view in cut

Source:The authors.

Figure 7. View from above



Source: Engineering Center of automotive industry.

Figure 8. Measurement points (F1 to F6)

The ceiling is prepared with an adhesive tape on the edges of the glass and the glue is placed over the tape. After the drying time of the glue, the operator measures the height and length of the glue with a pachymeter. The same ceiling is used for testing in the next daily collection.

MONITORING THE PROCESS

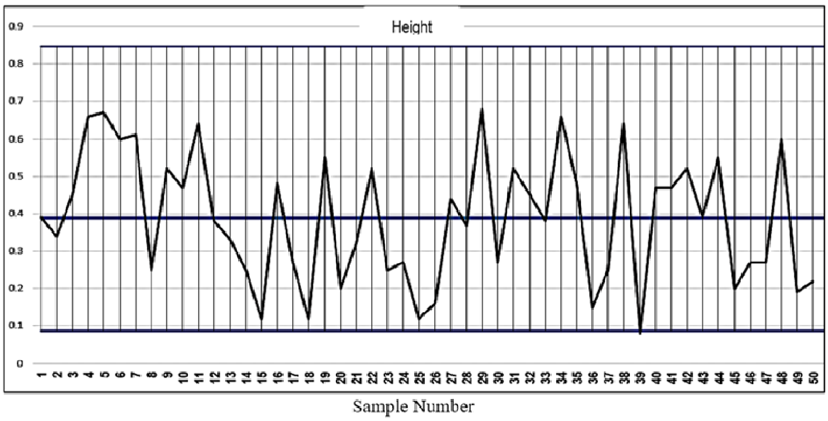
The main contribution of this paper is to estimate the control limits for the control graph of $\overline{X}$ andR.During the period of samples collection for construction of process control charts, it is subject to recurrence of special causes; so, it is reasonable to start the construction of the control charts by the amplitude plot. The statistic $\overline{R}$ used to estimate σ_0 is insensitive to special causes that change only the average of the process. In order to estimate the control limits, the concept of rational subgroups was followed, recommending the withdrawal of small samples at regular intervals (13,14). 50 samples of size n = 6 were selected for the construction of GC R (see Appendix A). With the process free of special causes, the limits for GC R were estimated using the approach discussed in Sampaio (8). The standard deviation of the process was estimated by the equation: $\hat{\sigma}_0 = \overline{R} / d_2$. The estimated standard deviation of the height variable was $\hat{\sigma}_{0,altura} = 0.3892 / 2.534 = 0.153591$. The estimated standard deviation of the variable length was $\hat{\sigma}_{0,comprimento} = 0.6956 / 2.534 = 0.274507$. Traditionally, the use of k = 3 is used to control in which the average number of samples to occur a false alarm - NMA0 = 370.4, i.e. the risk $\alpha = 0.0027$. However, this result is not valid for GC R, since the sampling distribution of the amplitude is not normal. Applying the function presented in the appendix of Sampaio (8), we obtain the results of Figure 9.

```
GCR(6,370.4)

[1] "Winf"
[1] 0.57
[1] "Wsup"
[1] 5.52
              1      2      3      4      5      6      7      8
lambda   1.5000 2.0000 2.5000 3.0000 3.5000 4.0000 4.5000 5.0000
Poder    0.0967 0.3706 0.6242 0.7846 0.8753 0.9257 0.9542 0.9709
NMA     10.3460 2.6984 1.6020 1.2745 1.1425 1.0802 1.0480 1.0300
```

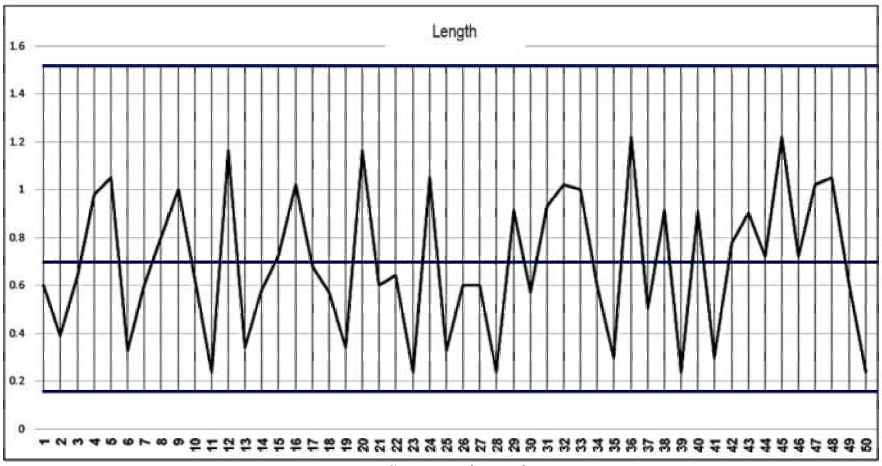
Source: The authors.

Figure 9. Result of applying the GCR function GCR (*n*, *NMA*$_0$) shown in the appendix



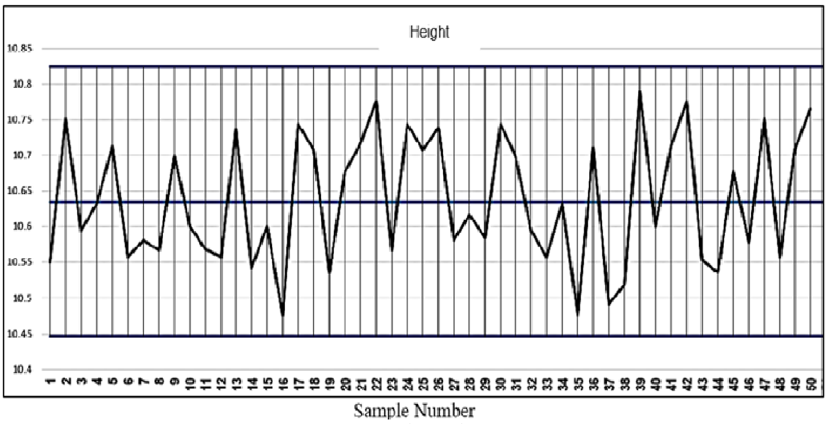
Source:The authors.

Figure 10. Amplitude Chart R - height



Source: The authors.

Figure 11. Amplitude Chart R - length

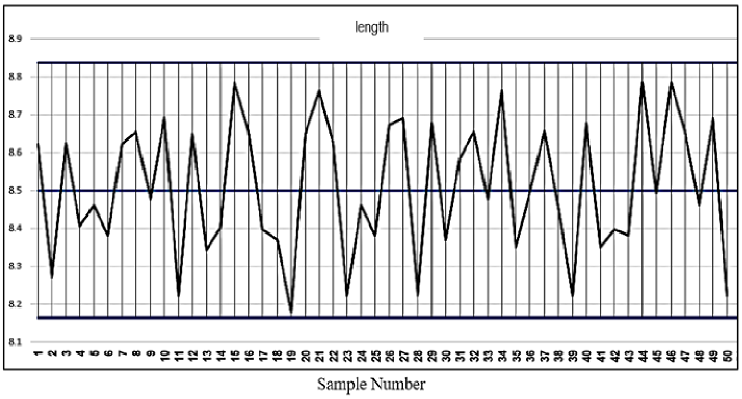


Source: The authors

Figure 12. Graph of average $\bar{X}$–height

Figure 9 provides the limits: w_{inf}= 0.57andw_{sup} = 5.52. According to the example, we would have $LCL_R = 0.57\hat{\sigma}_0$ and $LCL_R = 5.52\hat{\sigma}_0$. The estimated limits for GC are:

$$LCL_{R,\text{height}} = 0.0875; UCL_{R,\text{height}} = 0.8478; LCL_{R,\text{length}} = 0.1565; UCL_{R,\text{length}} = 1.5153$$



Source: The authors.

Figure 13. Graph of average X¯– length.

It is also observed in Figure 9 that for deviations of the order of $\sigma_1 = \lambda\sigma_0$, the power and the NMA of the GC R are presented. For example, if $\lambda = 2$, the chart takes an average of 2.6984samples to signal a special cause that causes change ($\sigma_1 = 2\sigma_0$) in the standard deviation of the process. Following the method proposed by Costa (7), when using the mean amplitude to estimate the variability of process, we are assuming that the process was in control during the withdrawal of samples; this hypothesis needs to be confirmed. If the amplitude of any sample is in the region of action of the control plot, a research work should be performed to diagnose the special cause that increased variability. This decision-making process is illustrated in Appendix B. Graphs for amplitude are shown in Figures 10 and 11. In the process, no points were identified in the region of action of control graphs, only the sample 39 of the height variable (Figure 10) presented a slightly lower value than the LIC. As this value does not indicate an increase in process variability, it was decided to maintain the limits calculated to monitor the application process of PU glue in automotive vehicles. After estimating the control limits of the graphs to monitor the amplitude R, it is necessary to estimate the limits of control of the graphs to monitor the average:

$$LCL_{\overline{X},\text{height}} = 10.6354\text{-}3\frac{0.15360}{\sqrt{6}} = 10.4473;$$

$$UCL_{\overline{X},\text{height}} = 10.6354\text{+}3\frac{0.15360}{\sqrt{6}} = 10.8235$$

$$LCL_{\overline{X},\text{length}} = 8.5011\text{-}3\frac{0.2745}{\sqrt{6}} = 8.1649;$$

$$UCL_{\overline{X},\text{Length}} = 8.5011\text{+}3\frac{0.2745}{\sqrt{6}} = 8.8373$$

The graphs for monitoring the mean are shown in Figures 12 and 13. In the process, no points were identified in the region of action of control charts, i.e. it is believed that the process is free of special causes that take the mean of value target. The estimated limits are indicated to monitor the application process of PU glue in automotive vehicles.

Final Considerations: The present study had as main objective to estimate the limits of control charts to monitor average and variability of a glass fixation process in an automotive vehicle. Differentiated methodology was used for the construction of control chart for sample amplitude. The estimation of a lower control limit makes it possible to evaluate if there is an improvement in the process, that is, if there is a reduction of variability. In addition, a suitable control for type I error was established in the control chart design, ie, the average number of false alarms is accurately calculated. Graphs to monitor the average value and amplitude of quality characteristics: height and length of the amount of glue are the main contributions present in the research. These charts can assist quality managers in monitoring and tracking this process in both the industry 4.0 and our current industry. Simultaneous monitoring of two or more variables hasbeen investigated by several authors (Leoni *et al*., 2015; Simões *et al*., 2016; , 15, 16, 17). This seems to be an interesting proposal for future research. Other proposals are: assessing the capacity of production process and adequacy of measurement system.

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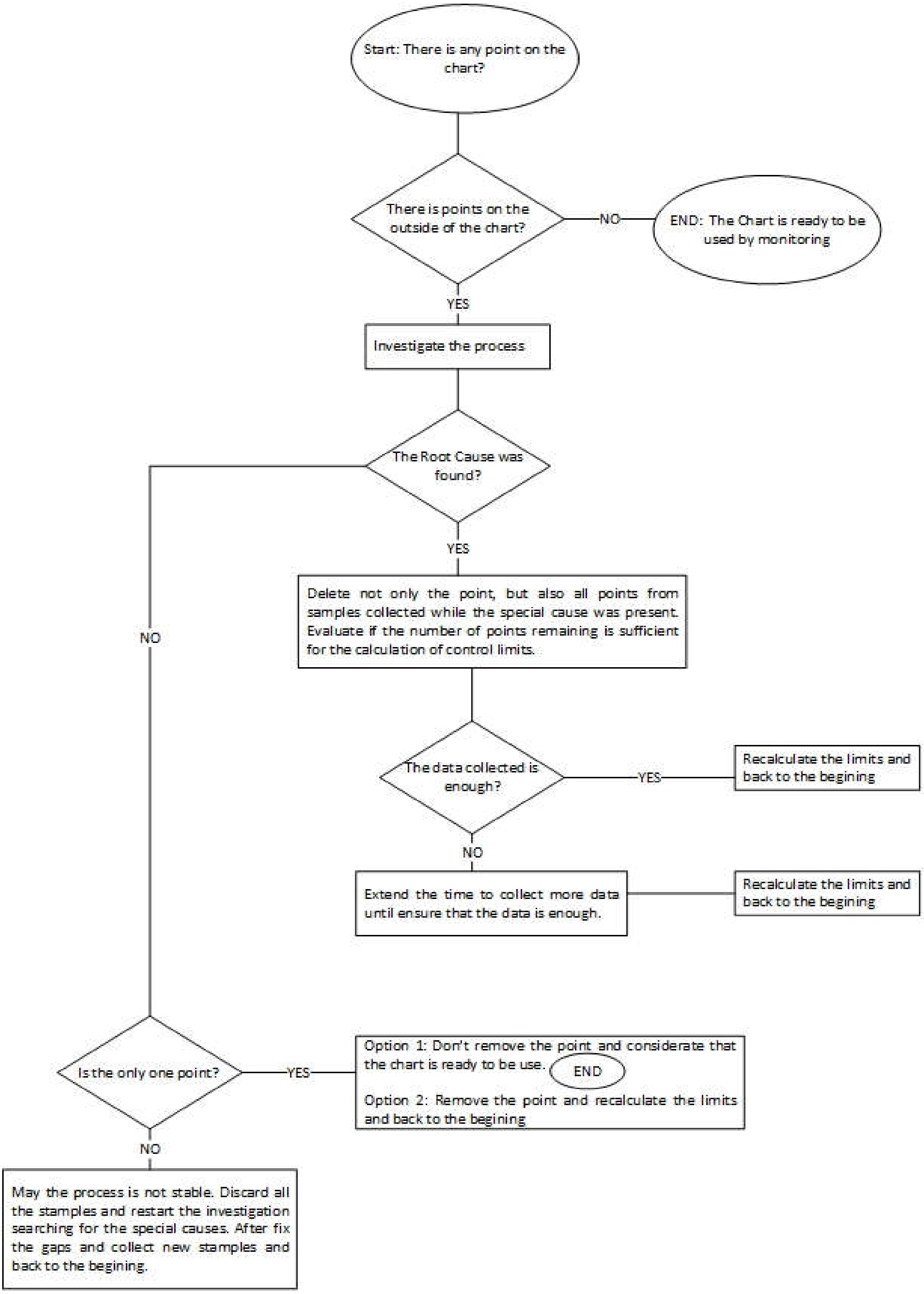
Appendix A–Samples of Height And Length Of Pu Glue Process On Panoramic Roof.

	HEIGHT						LENGTH					
SAMPLE	F1	F2	F3	F4	F5	F6	F1	F2	F3	F4	F5	F6
1	10.71	10.58	10.5	10.36	10.4	10.75	8.4	8.52	8.61	8.6	9	8.6
2	10.8	10.5	10.81	10.79	10.84	10.77	8.25	8.34	8.19	8.1	8.25	8.49
3	10.63	10.58	10.53	10.85	10.58	10.4	8.36	8.47	8.38	9	8.54	9
4	10.47	10.61	10.69	11.1	10.48	10.44	8.98	8.37	8.4	8.46	8.23	8
5	10.56	10.57	11.23	10.61	10.64	10.67	7.95	8.26	8.24	9	8.32	9
6	10.6	10.4	11	10.45	10.5	10.4	8.34	8.23	8.56	8.42	8.32	8.42
7	10.63	10.39	11	10.48	10.58	10.41	8.4	8.52	8.61	8.6	9	8.6
8	10.59	10.48	10.63	10.47	10.51	10.72	9	8.2	8.79	8.75	8.44	8.75
9	10.75	10.77	10.75	10.81	10.82	10.3	8.56	8.47	8.47	8.36	9	8
10	10.64	10.56	10.53	10.88	10.58	10.41	8.59	8.4	8.42	8.88	9.02	8.85
11	10.45	10.63	10.64	10.25	10.89	10.55	8.25	8.34	8.19	8.1	8.25	8.2
12	10.41	10.66	10.79	10.54	10.48	10.47	7.78	8.9	8.85	8.88	8.94	8.55
13	10.75	10.77	10.75	10.5	10.82	10.83	8.5	8.21	8.33	8.51	8.17	8.34
14	10.47	10.61	10.69	10.57	10.48	10.44	8.32	8.7	8.7	8.33	8.25	8.12
15	10.56	10.57	10.55	10.61	10.64	10.67	8.4	8.78	8.7	9	8.7	9.12
16	10.23	10.5	10.71	10.3	10.6	10.52	7.92	8.9	8.85	8.88	8.94	8.44
17	10.81	10.75	10.88	10.61	10.69	10.72	8.78	8.5	8.7	8.1	8.21	8.1
18	10.71	10.74	10.69	10.78	10.66	10.67	8.21	8.32	8.41	8.25	8.78	8.25
19	10.34	10.46	10.56	10.89	10.35	10.62	8	8.34	8.19	8.1	8.25	8.2
20	10.78	10.76	10.67	10.62	10.65	10.58	7.78	8.9	8.85	8.88	8.94	8.55
21	10.91	10.89	10.68	10.6	10.63	10.59	8.4	8.78	8.7	9	8.7	9
22	10.67	10.87	10.76	11.02	10.5	10.83	8.36	8.47	8.38	9	8.54	9
23	10.59	10.48	10.63	10.47	10.51	10.72	8.25	8.34	8.19	8.1	8.25	8.2
24	10.81	10.75	10.88	10.61	10.69	10.72	7.95	8.26	8.24	9	8.32	9
25	10.71	10.74	10.69	10.78	10.66	10.67	8.34	8.23	8.56	8.42	8.32	8.42
26	10.79	10.74	10.75	10.81	10.65	10.69	8.81	8.85	8.25	8.7	8.72	8.7
27	10.67	10.64	10.33	10.51	10.77	10.57	8.73	8.84	8.24	8.81	8.72	8.81
28	10.82	10.45	10.48	10.75	10.65	10.55	8.25	8.34	8.19	8.1	8.25	8.2
29	10.57	10.65	10.55	10.21	10.64	10.89	9	9.05	8.87	8.75	8.14	8.25
30	10.81	10.75	10.88	10.61	10.69	10.72	8.21	8.32	8.41	8.25	8.78	8.25
31	10.75	10.77	10.75	10.81	10.82	10.3	7.97	8.9	8.71	8.88	8.74	8.31
32	10.63	10.58	10.53	10.85	10.58	10.4	7.92	8.9	8.85	8.88	8.94	8.44
33	10.41	10.66	10.79	10.54	10.48	10.47	8.56	8.47	8.47	8.36	9	8
34	10.47	10.61	10.69	11.1	10.48	10.44	8.4	8.78	8.7	9	8.7	9
35	10.23	10.5	10.71	10.3	10.6	10.52	8.18	8.37	8.48	8.41	8.25	8.41
36	10.78	10.78	10.72	10.72	10.63	10.63	8	8.23	8.11	8.41	9.22	8.99
37	10.4	10.5	10.4	10.5	10.5	10.65	8.57	8.56	8.45	8.95	8.75	8.66
38	10.56	10.66	10.32	10.47	10.23	10.87	8.11	8.22	8.09	8.44	9	8.88
39	10.75	10.77	10.75	10.81	10.82	10.83	8.25	8.34	8.19	8.1	8.25	8.2
40	10.64	10.56	10.53	10.88	10.58	10.41	9	9.05	8.87	8.75	8.14	8.25
41	10.52	10.58	10.59	10.78	10.82	10.99	8.18	8.37	8.48	8.41	8.25	8.41
42	10.67	10.87	10.76	11.02	10.5	10.83	8.65	7.87	8.32	8.54	8.47	8.54
43	10.39	10.41	10.46	10.78	10.65	10.63	8.25	8.39	8.45	8.1	9	8.1
44	10.34	10.46	10.56	10.89	10.35	10.62	8.4	8.78	8.7	9	8.7	9.12
45	10.78	10.76	10.67	10.62	10.65	10.58	8	8.23	8.11	8.41	9.22	8.99
46	10.6	10.48	10.67	10.47	10.51	10.74	8.4	8.78	8.7	9	8.7	9.12
47	10.87	10.75	10.88	10.61	10.69	10.71	7.92	8.9	8.85	8.88	8.94	8.44
48	10.6	10.4	11	10.45	10.5	10.4	7.95	8.26	8.24	9	8.32	9
49	10.8	10.68	10.82	10.65	10.63	10.67	8.73	8.84	8.24	8.81	8.72	8.81
50	10.7	10.8	10.74	10.92	10.73	10.7	8.25	8.34	8.19	8.1	8.25	8.2

Appendix B -Stabilishment of limits for control chart.



Source: Adapted from Costa (Costa *et al*., 2005)

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