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Suitability verification of a roughness measurement process using measurement system analysis and the *CdI** capability coefficient

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ABSTRACT
This work evaluates a roughness measurement process through a comparative study of measurement system analysis and the application of the *CdI** capability coefficient, which was developed by the Tolerancing and Metrology Research Group, led by the first author of this article. This research proposes a systematic approach for using the *CdI** coefficient to assess the capability of the measurement processes.

Section: RESEARCH PAPER

Keywords: MSA; CdI*; capability; measurement process

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1. INTRODUCTION

Ensuring reliable measurements involves a series of interconnected steps that extend beyond simply having a suitable instrument or measurement system. It requires monitoring and controlling environmental conditions, using validated methods and suitable accessories, and employing qualified personnel. In the industry, two types of measurements are used to verify quality and quantify performance: measurements of products and measurements of processes [1]. When the data quality is low, the benefit of the measurement system is also low. Conversely, when the data quality is high, the benefit increases [2].

The dimensional and shape precision, reliability, and life cycle of the manufactured components are contingent on the quality of the processed surface. It is therefore necessary to examine the measurement process with a view to ascertaining its capabilities [3].

In this context, the objective of the Measurement System Analysis (MSA) is to ascertain the suitability of a measurement system for a given application [4].

The IQA (Instituto da Qualidade Automotiva) [4] states that an MSA study divides variability into two categories: location (which examines the system's tendency, linearity, and stability) and dispersion (which analyzes repeatability, reproducibility, and the R&R—Repeatability and Reproducibility—parameter). The R&R parameter is often considered the total variability of the measurement system, excluding part variation and process tendency [5].

In the industry, the most widely used method for determining the R&R parameter is the Average and Range Method, as it is the method recommended by AIAG, the Automotive Industry Action Group [6]. This method has extensive applications, particularly in circumstances where statistical software is not available [7].

Over time, several studies have been conducted on the suitability of measurement processes. For instance, Diering et al. [8] developed an MSA procedure that enables the calculation and online monitoring of measurement system characteristics. The main point is to collect samples for the MSA for the statistical process control chart. Samples are collected directly from the production line during the manufacturing process. Kamil and Pawel [9] proposed a modification to the equation that determines %R&R, whereby the lower specification limit of the tolerance is taken into consideration. Al-Rafaie and Bata [10] analysed measurements and process capability by %R&R.

As asserted by Dietrich [11], the uncertainty of the measurement process used to generate the capability and performance coefficients must be estimated before the coefficients can be significant. The capability of a measurement process is derived from the measurement statistical properties of a measurement process that operates in a predictable manner. Vasilevskyi et al. [12] proposed a technique to estimate the probability of the appearance of defective products through the adequacy and reproducibility coefficients of the production process. It is evident that, in consideration of the aforementioned indices, the probability of the production process or its characteristics not aligning with the stipulated requirements is determined. Tabisz [13] proposed a novel methodology for determining the relative measurement capability, whereby the variability of measurement results is not associated with the tolerance zone of the product characteristic, but rather with the variability of the production process standard. The proposed method considers a combined influence of systematic and random errors.

A further method of verifying the suitability of a measurement process involves the utilisation of specific capability coefficients for measurement systems. This includes the capability coefficient C_{dl}^{*} [14], [15], which was developed by our research group and is presented in equation (1).

The C_{dl}^{*} capability coefficient has been developed for application to both instruments and measuring systems, with the purpose of monitoring them in terms of behaviour over time. It encompasses both systematic and random components associated with the measurement process during this period of accompaniment, thereby enabling the verification of the capacity of a measurement process to meet a measurement demand with metrological reliability [15].

$$C_{dl}^{*} = \frac{U}{3 \cdot \sqrt{\left(\frac{s}{\sqrt{n}}\right)^2 + \left(\frac{U_{\text{cal}}}{k_{\text{cal}}}\right)^2}} \cdot l \,, \tag{1}$$

where: U = maximum allowed measurement uncertainty; s = sample standard deviation; n = sample size; U_{cal} = uncertainty inherited from the measuring instrument or measuring system, obtained directly from its calibration certificate; k_{cal} = coverage factor associated with the uncertainty U_{cal}, and l = variable that expresses the relationship between the indication average ($\bar{X}$) and the nominal value (VN), being assigned the value l_1, given by equation (2), if $\bar{X}$ is less than VN, or l_2, otherwise, according to equation (3). The maximum value of l is 1.

The variable l represents the systematic component of error in equation (1), that is, it is a sensitivity variable that expresses how far the indication average deviates from the nominal value [15].

$$l_1 = \frac{\bar{X}}{VN} \,, \tag{2}$$

$$l_2 = \frac{VN}{\bar{X}} \,. \tag{3}$$

The comprehensive analysis of measurement systems is one of the fundamental cornerstones of quality assurance. Unreliable measurement results can lead to two main problems: the acceptance of defective parts or the rejection of good parts, both of which negatively impact an organization's competitiveness [16].

The objective of this work is twofold: firstly, to verify the suitability of the roughness measurement process for surfaces obtained by planing processes; and secondly, to verify the convergence between the MSA and the C_{dl}^{*} coefficient. This will minimise costs and time spent on measurements and processing.

Figure 1. Planing operation.

2. METHODOLOGY

Initially, ten parts of carbon steel (specification ABNT 1020) were selected for the experiment, and the surfaces of these parts were planed using a horizontal shaper and a carbide tool, as illustrated in Figure 1. The cutting depth was set at 0.5 mm, and the cutting speed was fixed at 60 strokes/min. The roughness parameter employed was Ra [17].

The rugosimeter used in the measures has the following characteristics: model DR 130, $nominal\_range$ = 10 µm; $resolution$ = 0.01 µm; $cut\text{-}off$ = 0.25 mm / 0.8 mm / 2.5 mm, and uncertainty in measurement U_{cal} = 0.08 µm for a coverage factor k_{cal} = 2.0. The pieces were measured taking the reference $temperature$ = (20 ± 1) °C and $rel\_humidity$ = (50 ± 10) % [18], [19]. The maximum allowable uncertainty in measurement U = 0.025 µm, and the nominal value VN = 3.5 µm.

With regard to the MSA, the study of repeatability and reproducibility [20], [21], was conducted by two metrologists who measured ten samples on five occasions each. The procedure employed is illustrated in Figure 2, in which: σ_{repe} = estimate of the standard deviation for repeatability; σ_{repro} = estimate of the standard deviation for reproducibility; $R\&R$ = absolute parameter of repeatability and reproducibility and $\%R\&R$ = relative parameter of repeatability and reproducibility.

To apply the C_{dl}^{*} capability coefficient, the study was divided into three parts: i) considering all points measured by the two metrologists, ii) considering only the points measured by metrologist number one, and iii) considering only the points measured by metrologist number two to compare the results and verify the possible implications. The maximum allowable uncertainty in measurement (U_{cal}) has been determined to be 0.1 µm, which corresponds to approximately 33 % of the maximum allowable tolerance. To the statistical treatment of the measured data, the normality of the samples was initially verified, applying the Shapiro-Wilk test, the Kolmogorov-Smirnov test, and the Cramer von Mises test [22], [23], [24], [25], [26]. If the samples were approved by at least one of the tests, they were considered to originate from a population with a normal distribution. Subsequently, the verification of potential outliers in the samples was conducted through the implementation of the Dixon test (Q-test), the Grubbs test, and the Chauvenet test [27], [28], [29].

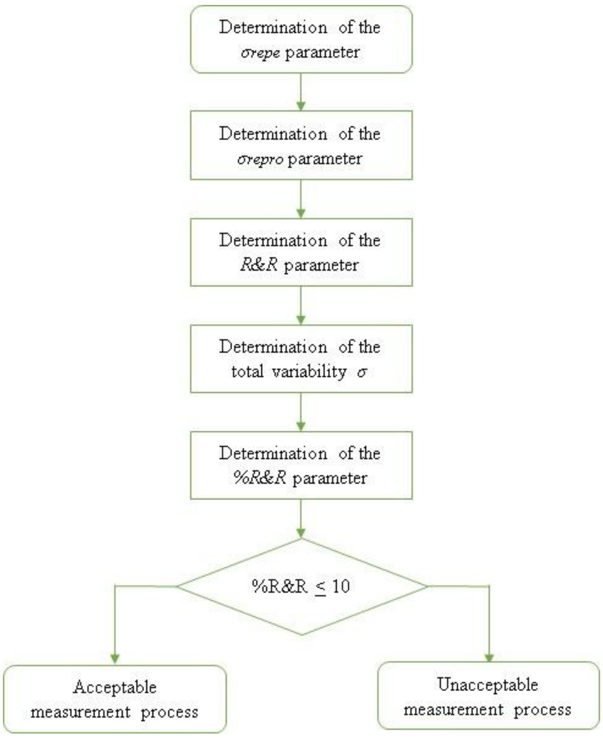

Figure 2. Stages of the repeatability and reproducibility study.

3. RESULTS AND DISCUSSIONS

The measurement data illustrated in Table 1 were generated by metrologist number one. Conversely, the measurement data shown in Table 2 were generated by metrologist number two. As illustrated in Table 3, the values of the variables employed in the calculation of the $\%R\&R$ approximate a figure of 86 %. As demonstrated in Table 4, the measurement process is considered to be unacceptable.

Table 1. Measurement data generated by metrologist number one.

Part	Roughness parameter Ra (µm)				
	x_1	x_2	x_3	x_4	x_5
1	3.23	3.69	3.68	3.39	3.31
2	3.36	3.24	3.61	3.52	3.08
3	3.02	3.85	3.23	3.03	3.38
4	3.35	3.40	3.19	3.13	3.30
5	3.31	3.35	3.67	3.20	3.40
6	3.29	3.61	3.37	3.02	3.16
7	3.09	3.15	3.07	3.31	3.33
8	3.93	3.39	3.96	3.77	3.08
9	3.32	3.52	3.73	3.33	3.60
10	3.23	3.10	3.02	3.45	3.42

Table 2. Measurement data generated by metrologist number two.

Part	Roughness parameter Ra (µm)				
	x_1	x_2	x_3	x_4	x_5
1	3.41	3.33	3.44	3.16	3.04
2	3.07	3.06	3.77	3.82	3.09
3	3.64	3.57	3.92	3.05	3.19
4	3.40	3.12	3.44	3.16	3.63
5	3.57	3.04	3.12	3.17	3.49
6	3.30	3.54	3.89	3.52	3.18
7	3.13	3.16	3.26	3.17	3.26
8	3.85	3.79	3.17	3.92	3.41
9	3.01	3.95	3.04	3.56	3.47
10	3.38	3.36	3.06	3.20	3.50

Table 3. *R&R* study parameters.

Parameter	Value
σ_{repe}	0.240 µm
σ_{repro}	0
$R\&R$	1.441 µm
σ	0.261 µm
$\%R\&R$	86.2%

Table 4. Classification of the measurement process.

$\%R\&R$	Decision
If $\%R\&R \leq 10\%$	Acceptable
If $10\% < \%R\&R \leq 30\%$	Partially acceptable
If $\%R\&R > 30\%$	Not acceptable

Figure 3 illustrates the interaction between the two metrologists, while Figures 4 and 5 present the mean and range charts per metrologist, respectively. It has been verified that all points are found within the control limits. The figures presented in Figure 3, Figure 4, and Figure 5 were generated using Minitab Software, version 19.

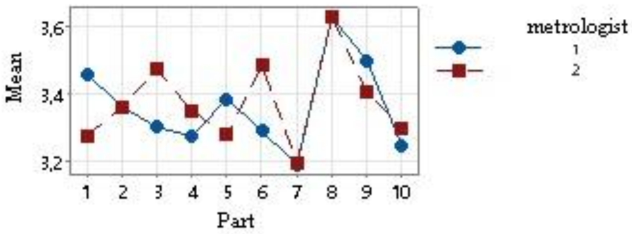

Figure 3. Interaction between the metrologists.

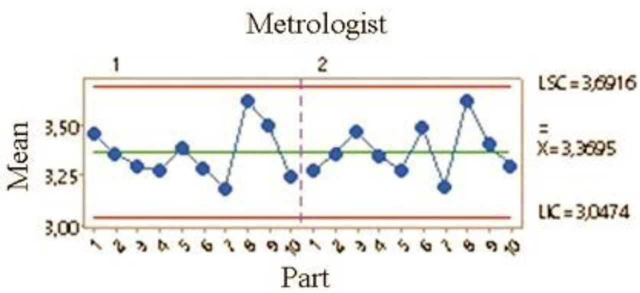

Figure 4. Mean control chart for both metrologists.

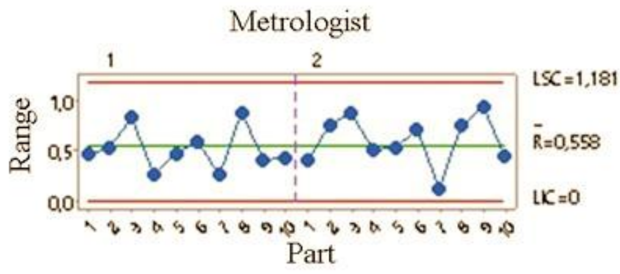

Figure 5. Range control chart for both metrologists.

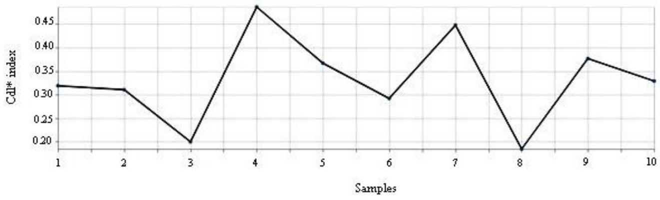

Figure 6. Variation of the capability coefficient *Cdl** for parts measured by metrologist number one.

Figure 7. Statistical process control chart for mean.

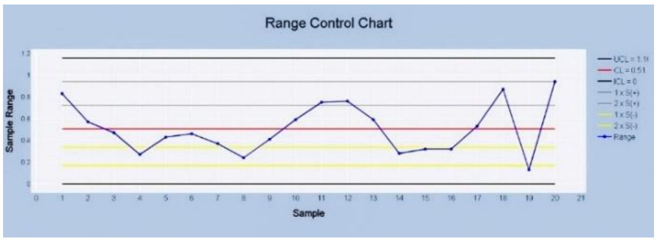

Figure 8. Statistical process control chart for range.

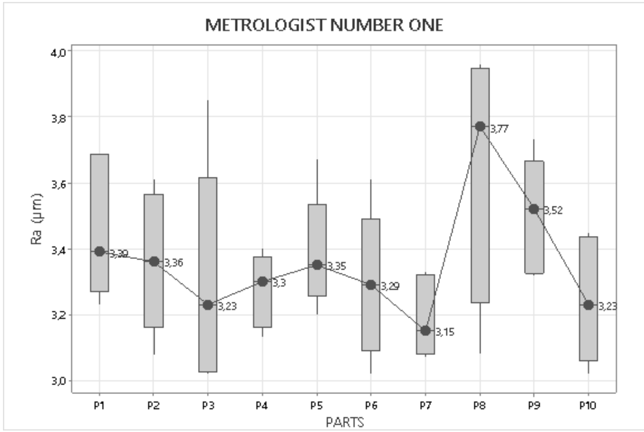

Figure 9. Measurement data generated by metrologist number one.

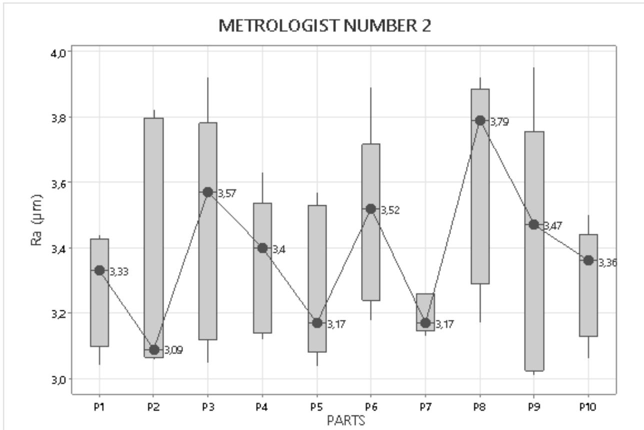

Figure 10. Measurement data generated by metrologist number two.

The C_{dl}^{*} capability coefficient was used to verify the roughness suitability. This was divided into three parts: i) all measured points (n = 100) with C_{dl}^{*} = 0.67, ii) metrologist number one's data (n = 50) with C_{dl}^{*} = 0.61, and iii) metrologist number two's data (n = 50) with C_{dl}^{*} = 0.57. The values of the capability coefficient were approximately equal for the three situations, and presented a result of inadequacy of the measurement process, since its value was less than 1.33, corroborating the results obtained through the R&R study. The C_{dl}^{*} coefficient can be calculated per sample as shown in Figure 6. This chart was obtained with data generated by metrologist number one, using the 3C Control Chart and Capability Software [30]. The C_{dl}^{*} did not remain constant for each isolated part, as shown in Figure 6. The graph shows all values lower than the C_{dl}^{*} value equal to 0.61, considering the fifty measured points.

In order to verify whether the manufacturing process was in statistical control, the 3C Control Chart and Capability Software [30] was used to generate the mean and range control charts, according to Figure 7 and Figure 8. With regard to the range chart, the process is under statistical control. However, with regard to the mean control chart, there is a point above the upper control limit, and it is also verified by six consecutive points going up and down, indicating that the process is out of statistical control, according to ISO 7870-2 [31].

Figure 9 shows the boxplot of the measurement data for the ten parts measured by metrologist number one. Figure 10 shows the boxplot for the data obtained by metrologist number two. A close analysis of the two figures reveals a marked variability from one piece to another, which may indicate a heterogeneity of the planed surfaces.

4. CONCLUSIONS

A thorough analysis of the data pertaining to the R&R study revealed that the standard deviation for reproducibility was found to be equal to zero. This outcome is attributed to the fact that both metrologists were adequately trained in measurement techniques and adhered to the same measurement procedure. Conversely, the standard deviation pertaining to repeatability exhibits a high value, which may signify an issue with the rugosimeter. However, this problem may be attributable to the planing stage, which resulted in surfaces exhibiting variations in surface finish, while maintaining the repeatability conditions in the manufacturing process (the same operator, the same cutting conditions, the same machine tool, the same manufacturing procedure, the same cutting tool, and the same environmental conditions). One potential explanation for this phenomenon is that the object in question is a very old horizontal shaper.

In order to verify the stability of the process, mean and range control charts were generated. A thorough examination of the charts in question has led to the conclusion that the process is not under statistical control. This finding lends further support to the hypothesis that the issue resides not with the rugosimeter itself, but rather with the manufacturing process. Consequently, prior to undertaking an R&R study or a capability study, it is imperative to ascertain whether the manufacturing process is under statistical control.

Upon examination of the variation chart of the C_{dl}^{*} coefficient for the data of metrologist number one, a variation is confirmed for each part ($n = 5$). However, it is reasonable to calculate the capability coefficient for all points measured by each metrologist. The C^*_{dl} value was equal to 0.61 for all data of metrologist number one. Utilising the arithmetic mean of the ten C^*_{dl} values presented in Figure 6 would result in C^*_{dl} being equivalent to 0.33. This value represents a difference of approximately 51 % for the C^*_{dl} value equal to 0.61.

AUTHORS' CONTRIBUTION

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