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Quality Control of Measurements Using the Repeatability and Reproducibility (R&R) Method

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Abstract
This study examines the use of the R&R (Repeatability and Reproducibility) method to improve measurement accuracy in quality control. By analysing single-operator (repeatability) and inter-operator (reproducibility) variability, the R&R method assesses overall system reliability. A case study on automotive part measurements shows acceptable variability levels but highlights repeatability as the main source of inconsistency. To enhance accuracy, the study recommends operator training, standardized procedures, regular calibration, and a stable measurement environment (consistent temperature, humidity, and low vibration). These improvements aim to reduce variability and increase system reliability, ensuring more precise quality control. The findings demonstrate the R&R method's value in identifying variability sources and guiding measurement process enhancements.

Keywords
Repeatability & Reproducibility method; measurement system variability; quality control, process standardization; parameters width and length.

Introduction

Measurement accuracy is a basis for quality control in production processes, as reliable data ensures that products meet required specifications and perform as intended. However, variations in measurement results can lead to inconsistencies in product quality, impacting customer satisfaction, safety, and compliance with industry standards. This article investigates the application of the R&R (Repeatability and Reproducibility) method, a measurement system analysis tool, which quantifies the precision of a measurement process by evaluating its repeatability (intra-operator consistency) and reproducibility (inter-operator consistency). By understanding and reducing variability within measurement systems, manufacturers can better control quality outcomes, optimize resources, and reduce costs associated with rework or product recalls.

The importance of this topic is underscored by the rapid advancements in manufacturing technologies, where production speed and complexity have increased, often with tighter tolerances on product dimensions. Ensuring that measurement systems provide accurate and reliable data across operators and conditions is therefore more critical than ever. This is particularly relevant in fields like automotive, aerospace, and medical manufacturing, where precise measurements directly affect the safety and functionality of products.

In modern measurement systems, ensuring accuracy and reliability is a critical challenge, particularly when dealing with high-sensitivity control diagrams. These diagrams are essential for monitoring both the position of the process and its variability. However, variations in measurement conditions, operator inconsistencies, and device calibration can significantly impact the reliability of measurement results. Addressing these challenges requires a structured approach that includes proper training, calibration, and environmental control.

Since the measurements of automotive parts were inaccurate and unreliable, defective parts were produced. The purpose of the case study is to determine what causes the defect problem. The problem may be inaccurate operator measurements, incorrect process standardization procedures, or inadequate environmental control. The only available data were operator measurement error data. For this reason, the Repeatability and Reproducibility (R&R) method was applied to assess operator error.

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Literature review

The analysis of key metrological characteristics, particularly repeatability and reproducibility, is essential for evaluating any measurement system. These characteristics help identify what influences measurement consistency, including factors related to operators and instruments. A common approach to assess these features is through a Gage R&R study, which determines how much of the variability in processes is due to measurement system variation.

Repeatability is the variation observed when the same operator measures the same part multiple times with the same instrumentation, whereas reproducibility considers the variation when different operators measure the same part with the same instrumentation. According to Gage R&R, total variability is separated into repeatability and reproducibility components, offering insight into the sources of measurement variation. A small variability in repeated measurements indicates good repeatability, while high variability among different operators points to poor reproducibility. Ultimately, Gage R&R studies verify that a measurement system is acceptable and fit for purpose (Zanobini et al., 2016; Montgomery, 2020; Catelani et al., 2014).

In the context of modern industries, particularly in sectors like automotive manufacturing, the necessity for reliable measurement systems has never been more pronounced. Businesses aim to minimize process variability to enhance productivity, recognizing that both the process itself and measurement system variability contribute to total system variability. Therefore, Gage Repeatability and Reproducibility studies serve a crucial role in ensuring the statistical reliability of these measurement systems (Gerger, 2021; Gerger & Firuzan, 2020; Saikaew, 2018).

Gage R&R (Deshpande et al., (2020) is a statistical method employed to evaluate the variation introduced by measurement devices and operators, a fundamental aspect of Measurement System Analysis (MSA). A robust measurement system should primarily account for product variation, with minimal measurement system contribution (Deshpande et al., 2020).

Effective implementation of Gage R&R requires careful consideration of the experimental design. It has been emphasized that creating homogeneous batches is critical for the successful execution of Gage R&R studies ((Sharma et al., 2019). Initial exercises in Design of Experiments (DoE) can facilitate understanding of key variables that affect the measurement process, further enhancing the measurement system's validation. While Gage R&R is a valuable tool, it is essential to recognize its limitations; it should be regarded as an aid rather than a comprehensive solution for measurement system validation (Sharma et al., 2019).

In the automotive sector, the precision of measurement systems is paramount. Accurate and automated measurement instruments are increasingly sought after to mitigate issues stemming from erroneous measurements, which can lead to significant financial losses (Ren, 2015). The application of methodologies like DMAIC (Define, Measure, Analyze, Improve, and Control) in conjunction with Gage R&R provides a structured approach to identify and rectify measurement system deficiencies. Notably, customers have reported issues with product specifications, highlighting the urgent need for effective measurement systems to maintain quality standards (Ren, 2015).

The principles of repeatability and reproducibility are equally relevant in the context of medical imaging. A study by (Jha et al., 2021) emphasizes the importance of evaluating the stability of imaging features across different acquisition parameters, arguing that only robust features should be used in predictive models to ensure their generalizability. Repeatability relates to consistency within repeated measurements, while reproducibility pertains to the stability of measurements across varied settings. Such distinctions are critical, as they highlight the inherent challenges in achieving reliable results in environments where conditions are not constant (Jha et al., 2021).

Moreover, the prevalence of R&R issues across various techniques and materials underscores the need for comprehensive analysis frameworks (Dowling et al., 2020). The dynamic nature of operations, particularly in manufacturing contexts like rolling bearing production, complicates the evaluation of measurement accuracy. Studies show that utilizing Gage R&R can effectively pinpoint the most reliable measurement systems, thereby improving overall measurement accuracy (Dowling et al., 2020).

Furthermore, recent advancements in graphical tools for Gage R&R analysis have been proposed to enhance understanding of measurement system variability. These tools are intended to provide deeper insights into the measurement process, thereby fostering improved practices in repeatability and reproducibility analysis (Wrzochala & Adamczk, 2019). Such innovations are crucial, especially as they enable more detailed evaluations of measurement systems, revealing potential areas for improvement (Malindzak et al., 2015).

Therefore the importance of repeatability and reproducibility in measurement systems cannot be overstated. From automotive applications to medical imaging, the consistency and reliability of measurement processes are foundational to quality assurance. As industries continue to evolve, ongoing research and development of methodologies and tools for R&R will remain vital to achieving high standards of accuracy and precision in measurements.

To ensure compliance with specifications and adequate product quality, measurement is an essential part of quality control. When measurement results are unreliable and inconsistent, it indicates an inadequate measurement process. To quantify the variability of the measurement system and its ability to provide accurate and reliable results, two important parameters should be applied: repeatability and reproducibility.

Repeatability indicates the variability of measurements performed by a single operator on an identical sample within a short period under the same conditions, verifying if a single operator's measurements are adequate (Markulík et al., 2022; Baleani et al., 2020).

Reproducibility identifies the variability of measurements performed by different operators on an identical sample under the same conditions, assessing if measurements are adequate across operators (Markulík et al., 2022; Baleani et al., 2020).

In the area of quality control, it is particularly appropriate to use control diagrams, especially for stably repeating production processes, where these diagrams can be used to identify random deviations that indicate non-fulfillment of quality limits. We distinguish 2 basic types of control diagrams, which are constructed for data obtained (Mikulová & Plura, 2019) by:

1. measurement
2. comparison.

To solve the problem outlined in this paper, control diagrams by measurement are applied. A characteristic feature of these diagrams is their high sensitivity. It is important to create a pair of graphs, one of which monitors the position of the process and the other describes the variability. By implementing these diagrams, we can identify sources of measurement inconsistencies and propose necessary improvements to measurement practices:

1. Control diagram for range – assesses the statistical control of the measurement process concerning variability in repeated measurements.
2. Control diagram for arithmetic means – verifies the suitability of the measurement system for evaluating variability between measured parts.

The limits of the control diagram can be calculated according to the following relations (Plura et al., 2023).

Control diagram for the selection range of variation (Plura et al., 2023; Plura, 2001; Malindzakova et al., 2023; Andrejiova, 2016):

$$\text{Test criterion: } R_j = x_{\max,j} - x_{\min,j} \tag{1}$$

Central Line (CL), Lower Control Line (LCL) and Upper Control Line (UCL):

$$\mathrm{CL} = \overline{R} = \frac{1}{k} \cdot \sum_{j=1}^{k} R_{ij} \tag{2}$$

$$\mathrm{LCL} = D_3 \cdot \overline{R} \tag{3}$$

$$\mathrm{UCL} = D_4 \cdot \overline{R} \tag{4}$$

where: CL – Central Line.
LCL – Lower Control Line.
UCL – Upper Control Line.
$\overline{R}$ – Average variation range.
k – Number of subgroup values, $i = 1, 2, 3, \cdots, k$.
D_3, D_4 – Constants for a certain range of subgroups, tables of the STN ISO 8258:1995 standard (ISO 8258:1991, 1991) Control diagram for the selection arithmetic mean (Plura, 2001):

$$\text{Test criterion: } \overline{x}_j = \frac{1}{n} \cdot \sum_{i=1}^{n} x_{ij} \tag{5}$$

Central Line (CL), Lower Control Line (LCL) and Upper Control Line (UCL):

$$\mathrm{CL} = \overline{\overline{x}} = \frac{1}{k} \cdot \sum_{j=1}^{k} \overline{x}_j \tag{6}$$

$$\mathrm{LCL} = \overline{\overline{x}} - A_2 \cdot \overline{R} \tag{7}$$

$$\mathrm{UCL} = \overline{\overline{x}} + A_2 \cdot \overline{R} \tag{8}$$

where: A_2 – Constant for a certain range of a subgroup, tables of the STN ISO 8258:1995 standard (ISO 8258:1991, 1991).

These control diagram (Figs. 1 and 2) follow a classic structure, featuring a central line and control limits.

The specification of control boundaries (limits), the central line, and the variation ranges of repeated measurements conducted by individual operators are presented in the control diagram (Fig. 1). For further evaluation, when the measurement process is statistically controlled in terms of variability of repeated measurements, all values in the variation range must

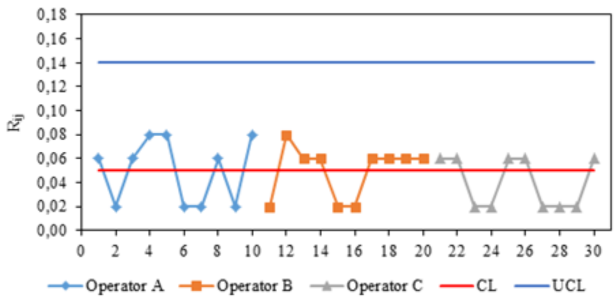

Fig. 1. Sample control diagram for variation range

fall within the control limits. If the process fails statistical control, two possible causes are identified (Plura, 2001; Andrejiova, 2016).

The first cause is the presence of a specific source of variability, where only one operator shows statistical inconsistency, indicating a deviation in their measurement method compared to other operators. The second cause is a specific increase in variability across repeated measurements, where all three operators display statistical inconsistency. This suggests that the measurement system is highly sensitive to operator actions, indicating a need for system improvements.

The suitability of a measurement system for assessing variability between parts can be established if more than 50% of the average values plotted fall outside the control limits, with operators consistently identifying the parts in question. In such cases, the measurement system can be considered adequate. The control diagram in Fig. 2 meets this criterion, with 73% of the average values lying outside the control limits and consistent measurements across operators (Plura, 2001).

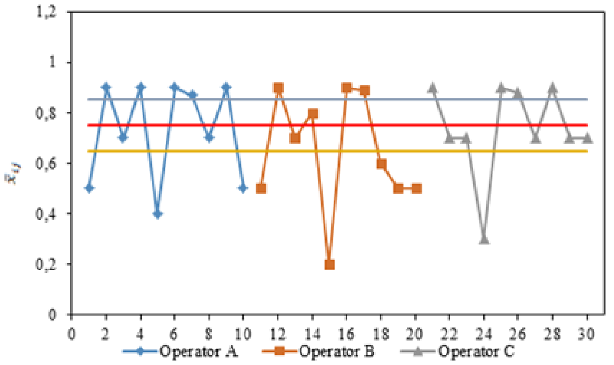

Fig. 2. Sample of a control diagram for the arithmetic mean

The R&R diagram provides valuable information for comparing individual operators. It details whether a specific evaluator is measuring more or less than the actual value and the variability of their measurements.

Problem definition

The problem defined in this article is the inaccuracy and unreliability of measurement processes in automotive part production, leading to defective components. The study investigates whether these issues stem from operator measurement errors, inadequate process standardization, or insufficient environmental control, using the R&R method to assess operator-related variability. This article seeks to offer targeted recommendations for reducing measurement inconsistencies through operator training, equipment calibration, process standardization, and environmental control.

The article includes a case study focusing on a digital caliper's measurements of an automotive part, demonstrating how R&R analysis can identify and mitigate sources of variability in repeated measurements. The study's findings emphasize the role of operator training, standardization of procedures, regular equipment calibration, and environmental control in achieving consistent measurement accuracy.

In an era where quality standards continue to rise, the application of R&R methodology offers actionable insights into measurement system improvements. By implementing these improvements, companies can enhance their quality control processes, increase production efficiency, and maintain competitiveness in quality-sensitive industries. This article aims to highlight the practical significance of R&R analysis and provide recommendations for improving measurement reliability in various manufacturing contexts.

Materials & Methods

The method, known as R&R, originates from the English terms Repeatability and Reproducibility. For long-term measurements, the measurement process includes five phases (Plura et al., 2023; Plura, 2001):

1. Select three operators (designated A, B, C) and ten samples (numbered 1 through 10).
2. Operator A measures all ten samples in random order.
3. The same procedure is repeated for operators B and C.
4. Repeat steps 2 and 3 for a second measurement.
5. Repeat steps 2 and 3 for a third measurement.

In the evaluation phase, data processing begins with the calculation of sample variability (PV) and then (Plura, 2001):

$$R_p = \max \overline{x}_j - \min \overline{x}_j; \quad j \in (1;r) \tag{9}$$

$$\mathrm{PV} = 5.15 \cdot \sigma_p = 5.15 \cdot \frac{R_p}{d_2^*} \tag{10}$$

where: $\max \overline{x}_j$ – maximum value from the arithmetic averages of all measurements of individual pieces

$\min \overline{x}_j$ – minimum value from the arithmetic averages of all measurements of individual pieces

σ_p – standard deviation of the sign values of the measured pieces

R_p – value of the variation range of the arithmetic means of all measurements for individual pieces

d_2^* – coefficient depending on the number of measured pieces

Calculation of percentage variability of samples %PV (Plura, 2001):

$$\%\mathrm{PV} = \frac{\mathrm{PV}}{\mathrm{TV}} \cdot 100 \tag{11}$$

Calculation of total variability (TV) (Saikaew, 2018):

$$\mathrm{TV} = \mathrm{USL} - \mathrm{LSL} \tag{12}$$

where:
USL – Upper Specification Limit.
LSL – Lower Specification Limit.

Following this, values for repeatability and reproducibility can be calculated:

- Repeatability (EV) calculation (Plura, 2001):

$$\mathrm{EV} = 5.15 \cdot \sigma_e = 5.15 \cdot \frac{\overline{\overline{R}}}{d_2^*} \tag{13}$$

where:
σ_e – is the repeatability standard deviation
d_2^* – is a coefficient based on the number of repeated measurements, the number of measured parts, and the number of operators

- Reproducibility (AV) calculation (Plura, 2001):

$$\begin{aligned} \mathrm{AV} &= \sqrt{(5.15 \cdot \sigma_0) - \left(\frac{EV^2}{n \cdot r}\right)} = \\ &= \sqrt{\left(5.15 \cdot \frac{R_0}{d_2^*}\right) - \left(\frac{EV^2}{n \cdot r}\right)} \end{aligned} \tag{14}$$

where:
σ_0 – is the reproducibility standard deviation
r – the number of measured parts
n – number of repeated measurements
d_2^* – the coefficient depending on the number of operators

The combined value for R&R is calculated as follows R&R (Plura, 2001):

$$\mathrm{R\&R} = \sqrt{\mathrm{EV}^2 + \mathrm{AV}^2} \tag{15}$$

The percentage values for repeatability (%EV) is calculated as follows (%EV) (Plura, 2001):

$$\%\mathrm{EV} = \frac{\mathrm{EV}}{\mathrm{TV}} \cdot 100 \tag{16}$$

The percentage values for reproducibility (%AV) is calculated as follows (%AV) (Plura, 2001):

$$\%\mathrm{AV} = \frac{\mathrm{AV}}{\mathrm{TV}} \cdot 100 \tag{17}$$

And the percentage values and R&R (%R&R) are then determined (Plura, 2001):

$$\%\mathrm{R\&R} = \frac{\mathrm{R\&R}}{\mathrm{TV}} \cdot 100 \tag{18}$$

The sum of all three values, %EV, %AV, and %R&R, is not 100%. If the R&R value is unsatisfactory, it is necessary to evaluate the share of %EV and %AV. Two scenarios can occur: if the %AV value is higher, the focus should be on the operators; if the %EV value is higher, attention should be directed to the measuring equipment. The following criteria exist for evaluating the %R&R value (Plura, 2001):

- %R&R $\leq$ 10% – system is capable if R&R meets the requirements.
- 10 $<$ %R&R $\leq$ 30% – system is conditionally capable if R&R meets partial requirements.
- %R&R $>$ 30% – system is incapable if R&R is below standard.

Results

In this case study, a plastic mold (Fig. 3) for automobile license plate frames was measured using a digital caliper.

Fig. 3. Plastic molding – mounted on passenger cars

Two parameters were measured based on customer specifications:

- product width: 168.5 mm with a tolerance of ±0.4 mm
- product length: 364.4 mm with a tolerance of ±0.45 mm

Three operators assessed these parameters on ten products, each measured independently three times.

Initially, the width parameter was evaluated. The first step in assessing the measurement system is verifying statistical control in repeated measurements. A control diagram was applied diagram (Fig. 4), showing that all points are within control limits, indicating that the process is statistically controlled.

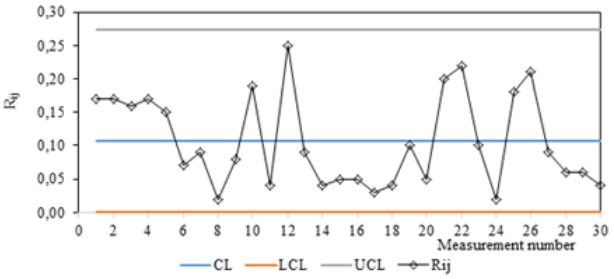

Fig. 4. Evaluation of variability in repeated measurements, parameter width

Following the initial phase, it is necessary to evaluate the process in terms of variability among the measured parts. This assessment is presented in Fig. 5, Evaluation of Variability Among Parts, Parameter Width. In this case, a specific type of control diagram is used, in which it cannot be predicted that all points will lie within the control limits. This can be represented by calculating the control limits based on within-subgroup variability. The system is suitable if more than 50% of the values fall outside the control limits, with confirmation required regarding which parts these represent for each operator. In this particular case, 19 points are outside the control limits, 4 points are on the boundary, and only 6 points are within the limits. It is also possible to observe consistency among the individual operators regarding the specific parts outside the control limits. For this reason, the measurement process for the width parameter can be considered suitable.

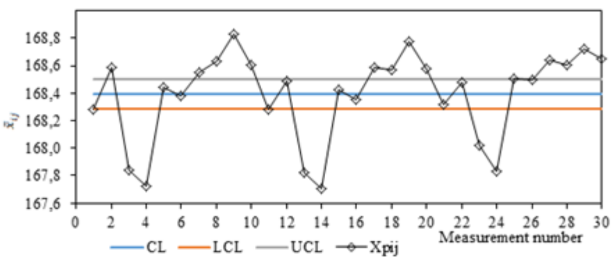

Fig. 5. Evaluation of variability among parts, parameter width

After evaluating the variability of repeated measurements as well as the variability among parts, it is necessary to calculate the percentage expression of the repeatability and reproducibility of the measurement system. Table 1 presents the results in percentage terms for R&R, for the width parameter. The value of 8.96% indicates that the measurement system is acceptable. Given that the %EV value is greater than %AV, it means that the repeatability of the measurement, i.e., the measurement method itself, has a greater impact on the overall variability.

Table 1
Percentage expression for R&R, parameter width

%EV	%AV	%R&R
7.85%	4.32%	8.96%

The R&R diagram can also be presented graphically to evaluate the variability of repeated measurements by individual operators and to compare them with other operators. In terms of the arithmetic mean of measurements by each operator, the best results were achieved by the first operator. Figure 6 also indicates that, in terms of average, the third operator has the worst result, as their mean value of 0.04 is above the overall average, although they have the same variability as the first operator. This implies that the third operator performs worse than the first two.

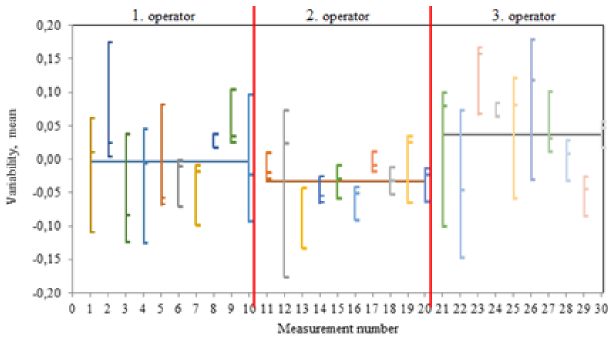

Fig. 6. R&R diagram, parameter width

In the same way as for the width parameter, an evaluation was carried out for the second parameter, i.e., length.

The evaluation process is the same, meaning that it is first necessary to verify whether the measurement process is statistically controlled in terms of the variability of repeated measurements. Figure 7 shows that all points are within the control limits, which indicates that the evaluation can proceed.

Subsequently, a control diagram was constructed for the arithmetic means of repeated measurements for the variability between the measured items. Figure 8 shows that the system is not suitable because seventeen points are outside the control limits, one is on the limit, and only eleven points are within the control limits. Given that more than 50% of the points are outside the control limits, it can be stated that the same items are being compared.

The resulting %R&R value for the length parameter (Tab. 2) is 5.09%, which is lower than the maximum acceptable value for a measurement system, i.e., 10%. From this, it can be concluded that the influence of %EV (equipment variation) and %AV (appraiser vari-

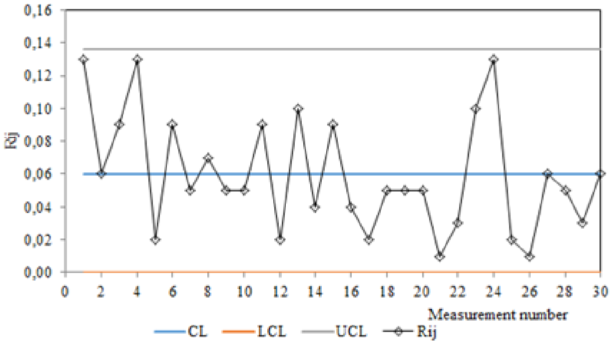

Fig. 7. Assessment of the variability of repeated measurements, parameter length

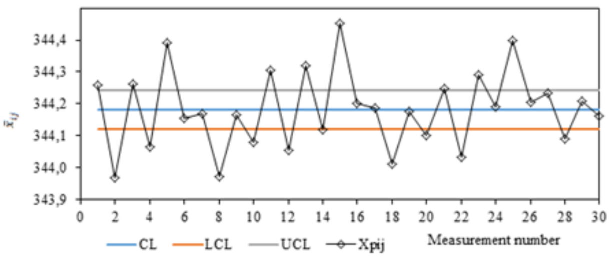

Fig. 8. Assessment of variability between items, parameter length

ation) is more or less balanced. The %EV value is slightly higher; therefore, the impact of repeatability is slightly greater.

Table 2
Percentage expression for R&R, parameter length

%EV	%AV	%R&R
3.92%	3.25%	5.09%

Figure 9 illustrates the graph for the assessment of repeatability and reproducibility and simultaneously explains that the second operator achieves the best results in terms of variability as well as the average of the measurements. The average value of the second operator is only 0.01 higher than the value of the overall average.

The results of the evaluation indicate that there are currently no issues in the manufacturing process, as the results of both assessments show that the measurement system can be accepted without any reservations. To improve the measurement system, it is important to focus on enhancing the conditions related to measurement, but attention must also be given to the measurement methods.

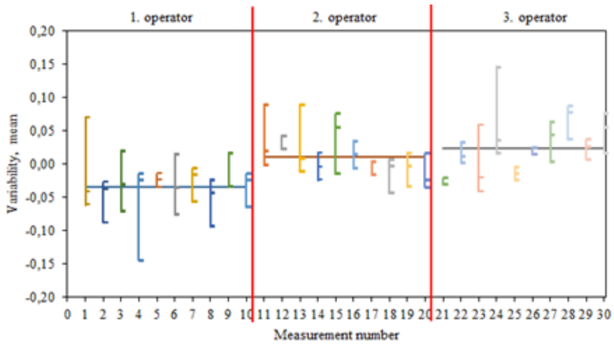

Fig. 9. R&R diagram, length parameter

Conclusions

From the results of the R&R method for ensuring accurate and reliable measurement, several improvements can be suggested. First, it is essential to provide thorough training for operators in the use of measuring equipment. In the case study, this specifically pertains to the digital caliper, and adherence to measurement procedures can significantly reduce measurement variability. Additionally, regular calibration of the measuring devices is crucial to ensure their accuracy and reduce the risk of erroneous measurements.

Another important improvement involves the standardization of the measurement process, which focuses on creating and adhering to standard measurement procedures. This standardization emphasizes the elimination of variability caused by different approaches of operators. Finally, controlling the measurement environment is vital, as it includes ensuring stable conditions such as temperature, humidity, vibrations, and other factors. These measures are directly based on the research findings, highlighting the necessity for device calibration and controlled conditions to minimize variability.

The significance of these findings lies in their potential to enhance the overall reliability and accuracy of the measurement system, reducing variability and ensuring compliance with industry standards. Implementing these improvements will ultimately lead to better quality control, reduced costs, and improved customer satisfaction in industries where precise measurements are crucial.

Acknowledgments

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