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Analysis of measurement uncertainties in mechanical production and subsequent use for process stability control

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Abstract. In the current industrial environment, where quality is a key factor in competitiveness, the measurement and control of the stability of production processes plays a vital role. This work focuses on the analysis of measurement uncertainties in mechanical production and their subsequent use for process stability control. Measurement uncertainties are an inherent part of any measurement system, and their understanding and proper management are necessary to ensure the accuracy and reliability of production processes. The MSA (Measurement Systems Analysis) method enables the assessment of the capability of measurement systems and the identification of sources of variability. Emphasis is placed on the standard uncertainties of types A and B and the ways in which they affect the measurement process. The work also includes a description of the implementation of statistical process control (SPC) and its importance in maintaining a stable production process. SPC makes it possible to continuously monitor production processes and quickly identify deviations, leading to timely corrections and minimization of defects. To achieve these goals, quality tools such as the Ishikawa diagram, histogram, and Pareto diagram are used. This work provides a comprehensive view of the importance of measurement and data analysis in ensuring stability and quality in manufacturing processes.

1. Introduction

In today's dynamically developing industrial environment, production quality plays a key role in maintaining competitiveness in the market. With increasing demands on the accuracy and reliability of products, it becomes necessary not only to optimize production processes, but also to consistently monitor and manage their stability. Manufacturing companies face pressure to ensure high levels of quality while reducing costs and shortening production cycles. This requires advanced methods of inspection and quality control that enable the rapid identification of deviations and the implementation of corrective measures. In this context, measurement is an essential tool, the results of which provide the necessary data for making decisions about product quality. However, no measurement system is perfect and is subject to various kinds of uncertainties that can significantly affect the final results. Understanding and properly managing these uncertainties is essential to ensure measurement accuracy and manufacturing process reliability. Measurement uncertainties can be both random, resulting from variable conditions during measurement, and systematic, caused, for example, by errors in meter calibration or environmental influences.

Measurement System Analysis (MSA) is a method that provides tools for evaluating the capability of measurement systems and identifying sources of variability. Through MSA, problems such as bias, stability, linearity, repeatability and reproducibility of measurements can be revealed, which can have a major impact on the quality of measurements. Identifying and eliminating these sources of variability is key to achieving reliable results and maintaining controlled manufacturing processes. Statistical process control (SPC) is also a part of modern quality control, which enables continuous monitoring of production processes and quick detection of deviations from the required standards. SPC uses tools such as control charts and capability indexes to monitor process performance and identify potential problems early. The introduction of SPC into the production process not only increases the quality of production, but also contributes to the efficient use of resources and the reduction of costs associated with production errors [1-2].

This article focuses on a comprehensive approach to measuring and controlling the stability of production processes, with an emphasis on the analysis of measurement uncertainties and their influence on process stability. It also describes the implementation of SPC methods and the use of quality tools such as the Ishikawa diagram, histogram and Pareto diagram, which play a key role in identifying and eliminating the causes of production problems. On the basis of practical examples from the field of engineering production, the importance of these methods in achieving high quality and stability of production processes is demonstrated [3-4].

2. Materials and methods

In this study, various quality methods and tools were used to analyze measurement uncertainties and stabilize production processes. The materials and methods used to achieve the stated goals are described in detail below.

2.1. Control plan

The control parts used in this study were produced on a lathe and their critical dimension was defined as 7.73 ± 0.02 mm (figure 1). This dimension is crucial because the optical lens is placed on the measured surface during assembly. The parts were made of aluminum alloy, which provides good machining properties and stability during subsequent operations.

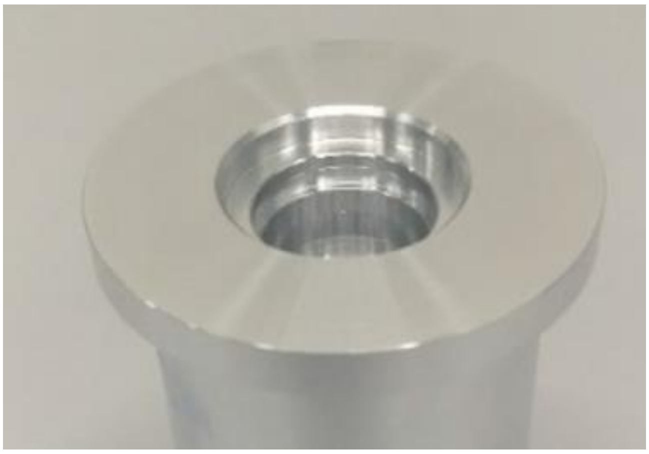

Figure 1. Measured sample.

2.2. Measuring instruments

A depth gauge was used to measure the critical dimensions, which allowed the dimension to be measured directly at the workplace on the lathe. Initially, a measuring system with a standard depth gauge was used, but due to problems with measurement stability and accuracy, this system was subsequently replaced by a more advanced device from Mahr (figure 2), which was equipped with special measuring tips and jigs for better measurement stability and accuracy [5].

Figure 2. Measuring system.

2.3. Data collection and analysis software
Minitab software was used for data analysis, which is a standard tool for performing MSA analysis using the Gage R&R (Repeatability and Reproducibility) method. Furthermore, MarCom Professional software from Mahr was used to collect data directly from the measuring device [6].

2.4. Measurement System Analysis (MSA)
The MSA method was used to evaluate the capability of the measurement system, which was crucial to ensure the accuracy and stability of the critical dimension measurement of the control parts. MSA included assessment of measurement repeatability and reproducibility, bias, stability and linearity. The first step involved performing an initial analysis of the existing measurement system, which identified significant sources of uncertainty, such as improperly selected measurement equipment and insufficient operator training. Based on these findings, corrective measures were designed and implemented, which included replacing the meter and implementing a new measurement procedure [7-8].

MSA is a method used to assess the capability of measurement systems. In this study, MSA was performed to identify and eliminate sources of variability that could negatively affect the critical dimension measurement results of control parts. The MSA process involved the following steps:

Determination of MSA objectives: The first step was to determine the objectives of the analysis, which was to ensure the repeatability and reproducibility of the measurements. It was decided to run the analysis on a sample of control parts under different conditions to identify any potential sources of variability.

Carrying out repeated measurements: The measurement was carried out several times by the same and different operators under the same conditions to determine the repeatability and reproducibility of the measurements. A standard measurement protocol was used, which included calibrating the measuring device before each measurement and recording all measured values.

Evaluation of results: The measured data were analyzed using Minitab software, where key statistical indicators such as standard deviation and fitness indices were calculated. The results indicated problems with the repeatability of the measurements, which led to the identification of necessary corrective actions [9-10].

2.5. Statistical Process Control (SPC)
SPC was introduced to monitor and control the production process in order to ensure the stability and quality of production. The SPC process involved the use of control charts and capability indices Cp and Cpk to continuously monitor the manufacturing process. The data obtained from the

measurements were regularly analyzed using MarCom Professional software, which enabled automated data collection and processing directly at the production site. Control charts were created to monitor the individual values of the measured parts and their variance, which enabled early identification of deviations and preventive interventions in the process.

SPC is a methodology that uses statistical tools to monitor and control manufacturing processes. In this study, SPC was implemented to ensure the stability of the production process and to reduce the variability between individual production runs. The SPC implementation process included:

Selection of monitored parameters: The critical dimension for SPC was the dimension 7.73 ± 0.02 mm, which was considered crucial for the quality of the final product. This parameter was monitored throughout the production process.

Creation of control charts: Control charts were created to allow monitoring of the dispersion of measured values over time. Control charts were used to identify deviations from standard values and to detect any extraordinary events that could affect the quality of the production process.

Evaluation of process capability: Using the capability indices Cp and Cpk, it was evaluated whether the process meets the required tolerances. The indices were regularly analyzed to identify any changes in process capability and take appropriate corrective action [11-12].

Cp (Process Capability Index) in context refers to how wide the range of dimensions (dispersion) is compared to the tolerance range. The Cp value will therefore offer whether the process variability (range of values) corresponds to the required tolerances. The higher the Cp value, the smaller the risk that the measured values will exceed the permitted limits.

Cpk (Positional Process Capability Index) within the context aims at whether the production takes place with a minimum of deviations from the desired center of tolerance. In the case of your process, this means watching to see if the 7.73 mm measured value stays close to that center without getting too close to the upper or lower tolerance limits (±0.02 mm). This is crucial because even a small offset from the center can cause some products to fall short of quality requirements.

2.6. Quality Tools

Quality tools such as Ishikawa diagram, histogram and Pareto diagram played a key role in identifying and analyzing the causes of problems in the measurement process. The procedure for their use was as follows:

Ishikawa Diagram: The Ishikawa diagram, also known as a cause-and-effect or "fishbone" diagram, was used as the first step in identifying possible causes of measurement accuracy problems. This diagram is particularly effective in structured analysis of complex problems where many different factors need to be considered. Evaluation of causes: After identifying the causes, individual factors were evaluated according to their probable influence on the overall instability of the measurement. This step helped select key areas to focus on for subsequent corrective actions. The Ishikawa diagram allowed a systematic breakdown of all potential factors affecting the measurement process, providing a solid basis for further analysis.

Pareto diagram: After identifying the causes through Ishikawa diagram, Pareto diagram was used to analyze them quantitatively. The Pareto chart, based on the Pareto principle (the 80/20 rule), helps to identify the small number of causes that have the greatest impact on the occurrence of problems. In this study, the procedure was as follows:

data collection and categorization: Based on the results from the Ishikawa diagram, each identified cause was quantified according to how often it occurs and how it affects measurement accuracy. The data were then sorted by frequency of occurrence or severity of effect.

creating a Pareto diagram: Subsequently, these causes were displayed in a Pareto diagram, where the horizontal axis displayed the individual causes (from the most frequent to the least frequent), while the vertical axis represented their cumulative effect on the measurement problems. A bar chart combined with a Lorenz curve (cumulative percentage influence) made it possible to visually identify which causes had the greatest influence.

Interpretation of results: The Pareto chart revealed that most problems with measurement instability were caused by several key factors, such as inappropriate selection of measuring instruments and insufficient operator training. Based on these results, specific corrective actions were recommended that focused on eliminating these dominant causes [13-14].

The Pareto diagram therefore played a vital role in focusing efforts on solving those problems that had the greatest impact on the quality of the measurements, allowing for more effective and targeted corrective actions.

Histogram: Histograms were used to visualize the distribution of measured data and to identify potential deviations from a normal distribution. A proper understanding of the data distribution is key to assessing whether the measurement system is operating within the expected parameters. The application of histograms in this study involved the following steps:

data collection: Data from the measurement of the critical dimension of 7.73 ± 0.02 mm was collected systematically during the production process. Each measurement was recorded in a database and subsequently analyzed using Minitab software.

creating a histogram: The measured data was divided into classes corresponding to specific intervals of values. For each class, the frequency with which a given dimension occurred was calculated and these values were subsequently displayed in the form of a bar graph. Each column in the histogram represented a certain interval of measured values, and its height corresponded to the frequency of these values.

Histogram Shape Analysis: The histogram shape was carefully analyzed to identify any abnormalities such as skewness, double-peaked distribution, or the presence of outliers. The histogram made it possible to visually assess whether the data is evenly distributed around the desired value or whether there are any systematic errors in the measurement.

Interpretation and Conclusions: The results from the histograms revealed that while most measurements fell within the expected range, there were some deviations that indicated possible problems with the repeatability of the measurements. These results led to recommendations for further tightening of control processes and calibration of measuring instruments.

The use of histograms provided deeper insight into the variability of the measurements and made it possible to identify specific problems that could be overlooked when analyzing numerical values alone.

3. Results and discussion

The figure 3 shows the results of the measurement system analysis using the Gage R&R (ANOVA) method in the Minitab program. This analysis is key to assessing the capability of the measurement system and identifying sources of variability.

Analysis of variance (figure 3) (Gage R&R): This graph shows how much noise or variability is introduced into the measurement system. The aim is to the resulting value to be as low as possible, which indicates less variability and better capability of the measuring system. Proportions of repeatability and reproducibility components: Graphs labeled 2 and 3 show the proportions of repeatability and reproducibility to total variability. It is important that the proportion of variability caused by differences between samples ("Part-to-Part") is substantially higher than the variability caused by the measuring system (Gage R&R). This means that the measurement system is able to distinguish between individual samples and is not the main source of variability.

R-Chart: This chart (marked with the number 5) shows the variance of the measured values between individual operators for each sample. Inter-operator variability should be minimal, indicating good repeatability.

Xbar-Chart: The chart (marked with the number 6) shows the average values measured by individual operators for each sample. Operators should have similar average values, and most of these values should lie within regulatory limits. If the averages are outside the control limits, this means that there is variability between samples, which is desirable because it indicates that the measurement system can distinguish between different samples.

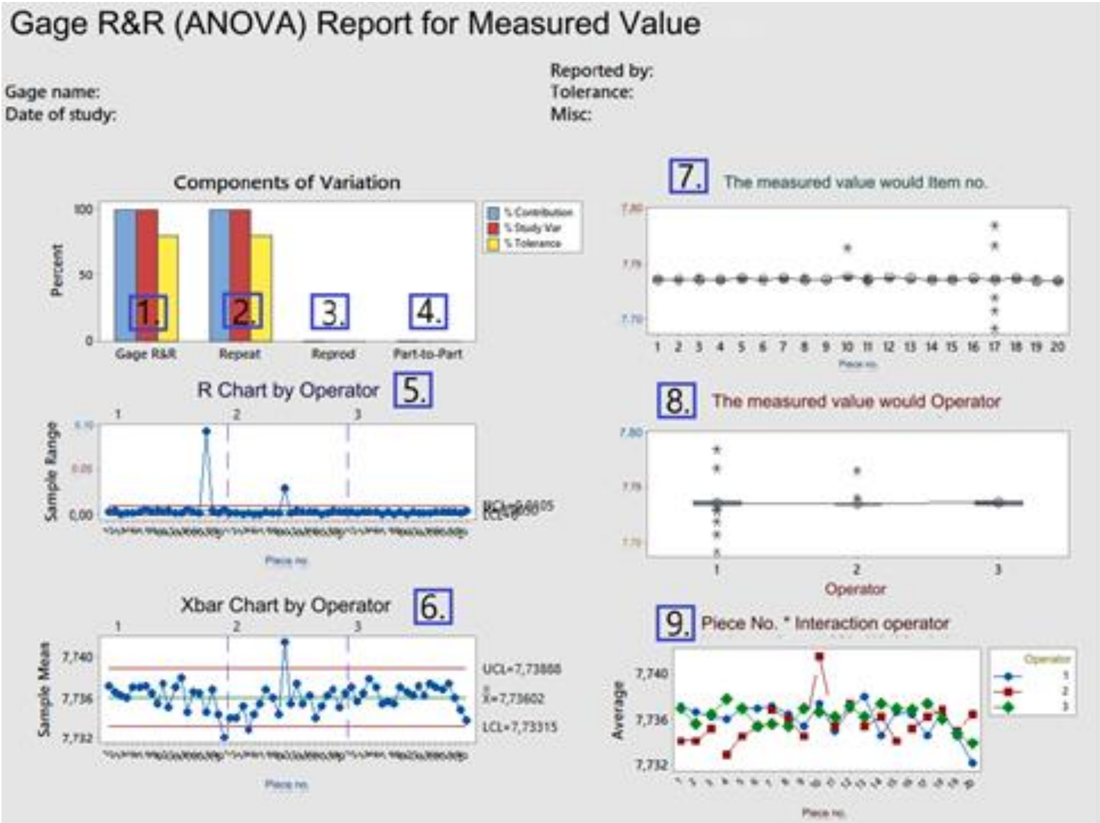

Figure 3. Measurement device.

Comparison of Samples and Variance of Values: This chart (labeled 7) shows the mean values and distribution of values for each sample. It would be ideal if the variance of the values for each sample were as small as possible, which would mean a low variability of measurements between operators.

Box-Plot for Operators: This diagram (marked with the number 8) compares the average values and the distribution of the measured values between operators. If the mean value curves are straight and similar, it means that the operators are measuring consistently and the measurements are reproducible.

Operator/Sample Interaction Plot: This plot (labeled 9) shows the interactions between operators and samples. If the curves are parallel, there is no interaction, which means that the operators are measuring the same mean value for the same samples. Any deviation from parallelism indicates interaction, which may mean that different operators are measuring the samples differently.

This analysis provides important information about the ability of the measurement system to measure reliably and about the consistency of measurements between different operators and samples. The aim is to minimize the variability caused by the measurement system and to ensure that all variability comes from differences between samples and not from imperfections in the measurement process. Based on the results of the analyses, specific corrective steps aimed at eliminating the identified problems were implemented. A new measurement method was chosen, which included the use of a modified gauge with higher stability, which significantly improved the repeatability and reproducibility of the measurements. In addition, more thorough training of operators was provided, focused on the correct use of meters and compliance with established procedures.

Based on the results of the MSA and SPC, corrective actions were implemented to eliminate the identified problems:

Replacement of measuring devices: The original measuring device was replaced with a more sophisticated device that allowed for more accurate and stable measurements. The new measuring system has been tested and calibrated to ensure its reliability and to minimize meter-induced variability.

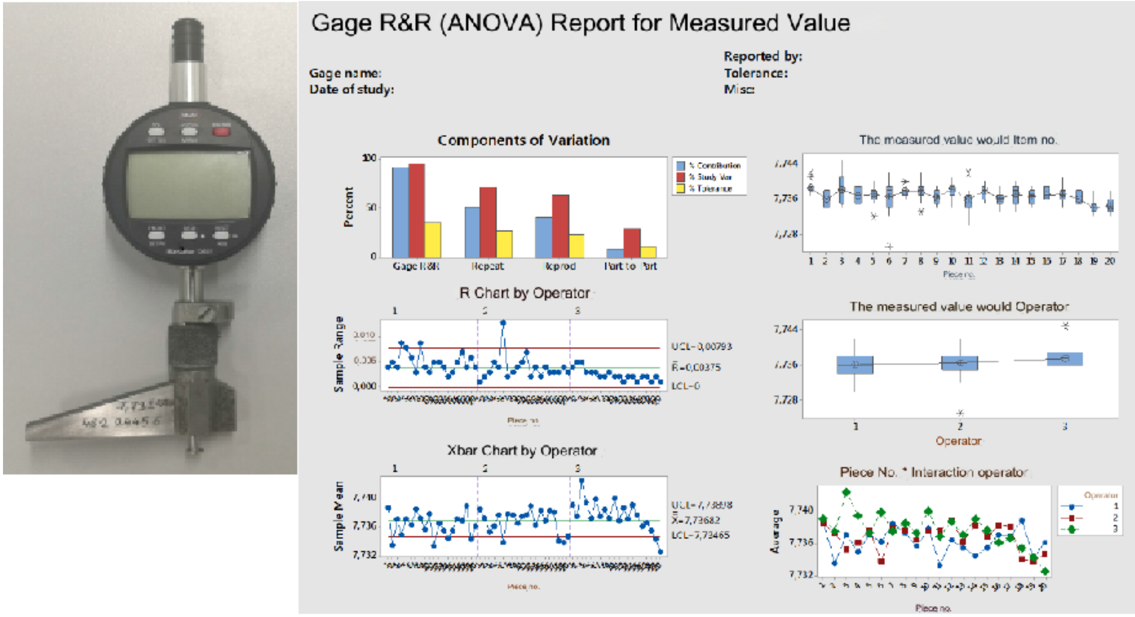

Figure 4. Analysis of the measurement system by the Gage R&R (ANOVA) method after the implementation of corrective measures.

Findings from measurements:

Shift in Gage R&R Variance Analysis (figure 4): The figure shows that there is some improvement after corrective measures are implemented. Although there has been a shift, the stability of the process still does not reach an acceptable level. The measurement variability is still too high, indicating that the measurement system is not completely reliable.

Unsuitability of the new meter: The new meter, which was modified from an originally different measuring device, presented unexpected problems. The modification, where one side of the gauge arm is shorter than the other, led to complications when placing the gauge on the measured surface of the product. This asymmetry could cause the contact surface of the gauge to deviate from the axis during the necessary pressure. In addition, the additional spring in the gauge arm could affect the stability and accuracy of the measurement.

Operator Issues: It was found that having to apply some pressure to press the gauge against the part led to hand fatigue which could affect the measurement, especially for operator #3 who was female. This problem manifested as a trend in the measurement results, suggesting that long-term use of the meter may cause measurement variability due to operator fatigue.

Follow-up: In view of these findings, it was decided to use a completely new gauge, which was assembled from a set of segments from Mahr. This new gauge allows for a choice of different length ground arms and a variety of gauge tips, which aims to improve stability and measurement accuracy and eliminate problems associated with the original gauge.

This analysis shows that despite the implementation of corrective actions, there are still issues with the measurement system that need to be addressed in order to achieve the desired level of process stability and measurement reliability. Follow-up steps include testing the new gauge to confirm its ability to address identified deficiencies.

After the introduction of the new meter (figure 5), which eliminated the original shortcomings, and the increase in the experience of the operators, there was a significant improvement in the stability of the measuring process. The results show an improvement in the repeatability and reproducibility of the measurements, which is crucial to ensure the reliability of the results. The share of the influence of the measured pieces on the overall variability of the process has also increased, which is a positive indicator because it means that the measuring system better distinguishes between individual pieces and is not the main source of variability.

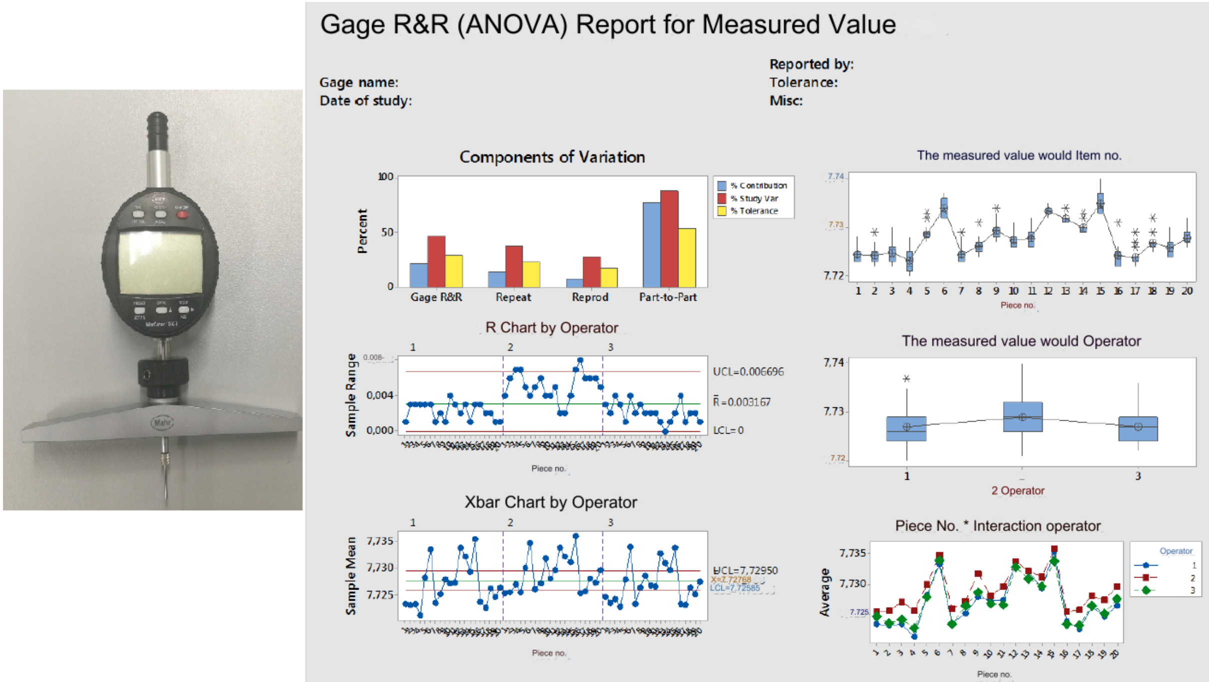

Figure 5. Analysis of the measurement system by the Gage R&R (ANOVA) method after the introduction of the new meter.

After implementing these measures, the value of total Gage R&R has decreased to just under 30 %, which is currently sufficient for the company and does not see the need for further investments in the measurement system. Although this result is considered satisfactory, a further step has been proposed to stabilize the process almost perfectly. This step involves the production of a hardened tablet that would be placed at the measured depth and then serve as a reference point for measuring the depth dimension. This approach would not only improve measurement accuracy, but also simulate the part's function in the overall assembly, allowing for a more accurate assessment of its suitability for assembly.

Overall, it can be said that the implemented measures have led to a significant improvement of the measurement process and the current level of stability is sufficient for the company. Another proposed measure could move the stability of the process to an even higher level, which would contribute to a further increase in the quality and reliability of the production processes. Thorough operator training focused on the correct use of the new measuring equipment and compliance with the established measurement procedures was carried out. These trainings helped reduce the human factor as a source of variability in the measurement process.

A new standardized measurement procedure was developed, which included regular calibration of the gauges, correct placement of the measuring device and control of the environment in which the measurement takes place. This procedure was put into practice and its compliance was regularly checked.

This study dealt with the analysis of measurement uncertainties in mechanical production and their subsequent use for managing the stability of production processes. In today's competitive industrial environment, quality is a key success factor, so it is important not only to optimize production processes, but also to ensure their stability through accurate measurement and effective control. In this context, measurement system analysis (MSA) is an essential tool for assessing the capability of measurement systems, which enables the identification and elimination of sources of variability such as bias, stability, linearity, repeatability and reproducibility of measurements.

4. Conclusions

The study dealt with a detailed analysis of measurement uncertainties in engineering production and their subsequent use for managing the stability of production processes. In the context of today's competitive environment, where quality plays a decisive role, it is crucial not only to optimize production processes, but also to ensure their stability through accurate measurement and effective management. Measurement System Analysis (MSA) and Statistical Process Control (SPC) have proven to be essential tools to achieve these goals.

The implementation of MSA allowed the identification of the main sources of variability in the measurement system, which led to significant improvements after the implementation of corrective measures. Specifically, the need to replace the existing meter with a more sophisticated device that was better adapted to specific measurement requirements was identified. This step led to an increase in the accuracy and stability of the measurements. Furthermore, improvements in operator training were key, helping to reduce the human factor as a source of variability. The introduction of a new standardized measurement procedure including regular calibration and correct placement of the measuring instrument has also significantly improved the quality of the measurement process.

The results of the study show that there was a significant improvement in the repeatability and reproducibility of the measurements after the introduction of the new meter and the improvement of operator experience. The overall share of Gage R&R has decreased to less than 30 %, which is currently an acceptable level for the company at which it does not see the need for further investment in measurement systems. This result is considered satisfactory because the measurement system now shows sufficient ability to distinguish between individual pieces and is not a major source of variability.

However, despite these improvements, another option was identified to further stabilize the measurement process. The proposed measure involves the production of a hardened tablet that would be placed at the measured depth and serve as a reference point for measuring the depth dimension. This approach would not only improve measurement accuracy, but also simulate the actual function of the part in the overall assembly, allowing for a more accurate assessment of its suitability for assembly. Such an innovation would further reduce the risk of incorrect measurement and increase the reliability of measurement results.

Overall, it can be stated that the measures taken significantly contributed to the optimization of the measurement processes, which led to higher stability and production quality. The introduction of MSA and SPC methods proved to be key to identifying and eliminating sources of variability, which enabled the desired level of production process stability to be achieved. The proposed additional measure in the form of a hardened tablet has the potential to push process stability to near-perfect levels, which would contribute to even higher quality and reliability of manufacturing operations.

These conclusions underscore the importance of continuous improvement of measurement and manufacturing processes in a competitive industrial environment. Ensuring a high level of quality is essential not only for maintaining competitiveness in the market, but also for the long-term sustainability and reliability of production operations. The company should continue to invest in improving its measurement systems and processes to ensure that it will be able to meet the increasing demands for quality and production accuracy in the future.

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