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COMPARATIVE STATISTICAL ANALYSIS OF MEASUREMENT RESULTS FOR CYLINDRICAL PART CHARACTERISTICS

Research paper

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Abstract: This paper aims to present a comparative statistical analysis conducted using two different software programs, Minitab and JASP, highlighting their capabilities, advantages, and limitations. The specific analysis was performed on cylindrical parts by measuring their characteristics with a coordinate measuring machine (CMM) and analyzing referent data using different statistical packages. The study demonstrates how the definition of the measurement task, combined with the shape of the workpiece and the choice of statistical software tool for data processing and analysis, influences the interpretation of output results and the drawing of conclusions. The contribution of this work lies in providing an applied comparative framework for evaluating statistical software in metrology, demonstrating how the choice of software tool can influence result interpretation and decision-making in engineering practice. Based on the analysis conducted, the paper can be used as a guideline for selecting appropriate software depending on the objectives of the statistical analysis.
Key words: Comparative statistical analysis, Coordinate measurement, Cylindricity tolerance, Measurement uncertainty, Design of Experiments, Statistical software tools.

INTRODUCTION

In modern manufacturing, the accuracy and precision of geometric characteristics of workpieces represent key factors for ensuring the quality and functionality of finished products (Genta, 2009; Tešić et al., 2023). The measurement of these characteristics, especially in cylindrical parts which are a common form in mechanical assemblies, requires the application of advanced measuring systems such as coordinate measuring machines (CMM), as well as appropriate statistical data processing. Statistical analysis plays a significant role in drawing conclusions about the correctness and stability of the production process. It plays a key role in detecting deviations, assessing process stability, determining the causes of variation, and validating the production process. In recent decades, there has been a growth in the use of specialized software packages for statistical analysis of measurement data. Minitab has long been used in industrial environments and is recognized for its reliability and ease of use (Pruett, 2009). In contrast, JASP is a relatively new open-source statistical software package that is gaining increasing popularity due to its user-friendly interface and support for advanced statistical analysis methods (JASP Team, 2023). Although both software tools provide similar statistical analysis capabilities, including analysis of variance, normality testing, regression analysis, and descriptive statistics, relatively few studies have focused on comparing the results obtained using these software packages (JASP Verification Project, 2023). Since different statistical packages can generate different results due to different algorithms, settings, approaches to data processing, or limitations in functionality, it is insufficiently explored how closely the results obtained in Minitab and JASP align in engineering applications. However, especially in precise technical analyses such as those in metrology, it is very important to know whether the choice of statistical software affects data interpretation.

The aim of this paper is to provide an answer to this question through the processing of results in both software packages, obtained through experimental analysis and measurements on a CMM. Special focus in the paper is placed on the influence of the software tool on the results of the analysis and the possibilities of interpreting those results. In addition to the introductory part, the following section presents the methodological part

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which explains the details of the measurement, comparison criteria, and software capabilities. Measurements were performed on real workpieces, and statistical processing was carried out in the mentioned software tools in parallel. Differences in the interpretation of results, user interface, flexibility, and applicability in engineering practice were analyzed. The results and discussion cover a comparative analysis of the results obtained in both software packages. Finally, the conclusion chapter presents key observations, advantages and limitations of both tools, as well as recommendations for future research. The motivation is to highlight, through this paper, the potential risks in the interpretation of statistical results when relying solely on one tool, without additional verification. This emphasizes the importance of combining measurement and statistical methods, as well as the role of software tools in making technical decisions.

MATERIALS AND METHODS

Methodology of conducted research began with defining the measurement strategy and selecting workpieces on which the measurements were performed. Measurements were carried out on a coordinate measuring machine (CMM), enabling high accuracy and precision of the data. The collected measurement data were analyzed in both software packages, Minitab and JASP, using the same statistical methods to ensure a relevant comparison of the results obtained. In addition to specific differences and demonstration of the application possibilities of these programs in appropriate statistical analyses, the research methodology also included an assessment of the user experience when working with the software, as well as the applicability for engineering purposes. Such approaches are commonly applied in manufacturing engineering, where experimental design methods are used for process optimization and parameter selection (Antony, 2014; Kramar et al., 2024).

Description of Measuring Parts

The experimental part of the research was performed on eleven different workpieces shown in Figure 1. These parts were processed using various machining procedures or processed using the same machining procedure but under different machining conditions, resulting in variations in the surface roughness of the machined surfaces. In this way, diversity in the measurement samples was ensured in terms of surface finish quality, which was defined as one of the input factors in the statistical analysis and allows for a more detailed interpretation of the results.



***Fig. 1**. Workpieces used for measurement*

Surface roughness of the workpieces used in the experiment was determined by measurement with a contact measuring device, a profilometer, manufactured by Mitutoyo. This device enables the measurement of surface roughness and waviness by establishing contact between the measuring probe and the measured surface, applying a measuring force, and moving along the measured profile at a constant speed. Figure 2 shows the measured roughness profiles for a cylinder processed by grinding (cylinder 1) and rough turning (cylinder 10).

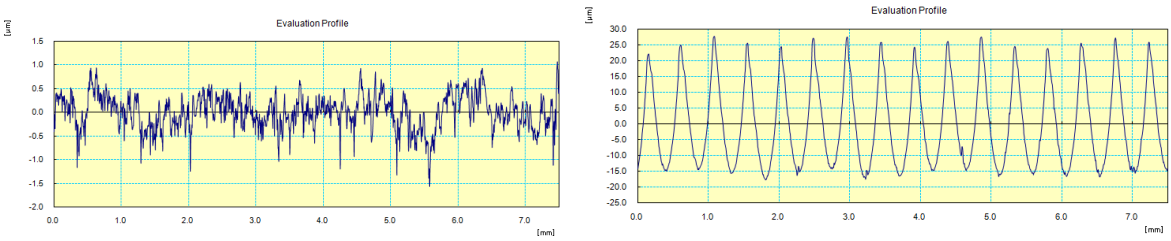


Fig. 2. *Measured surface roughness profiles of cylinders processed by grinding (cylinder 1) and rough turning (cylinder 10)*

Measuring System – CMM

Coordinate measuring systems (CMS) are highly flexible and efficient devices used to control the geometric characteristics of workpieces. Their operation is based on recording the coordinates of points on a workpiece in three-dimensional space to generate accurate measurement results. Coordinate measuring machines enable the assessment of all macro-geometric features on components of various configurations, with measurement ranges extending from micro- to nanometer scale. Due to these capabilities, coordinate measuring machines are widely used in both calibration laboratories and industrial practice (Štrbac, 2021; Hocken & Pereira, 2016; Zaimović-Uzunović et al., 2009).
For the purposes of this study, measurements were performed on a Carl Zeiss Contura RDS coordinate measuring machine. The CMM has a bridge structure. The available measuring range is 1000×1200×600 for the X, Y, and Z coordinates. The RDS head is rotary and can occupy any angle in space, and measurements can be performed in both modes: point-by-point and scanning. The CMM uses Calypso software support, which allows defining complex measurement tasks and performing analyses according to specified parameters.

Definition of the Experiment and Data Collection Strategy

When measuring cylindricity, there are several possible paths that the measuring probe can follow during point sampling, which define different measuring strategies. Among the most used are strategies based on generated lines, circular profiles, grids, point distributions, and spiral paths (Humienny et al., 2001; Weckenmann & Knauer, 1998). For this experiment, a point sampling strategy in the shape of a spiral on the outer diameter of the cylinder was selected, as shown in Figure 3.

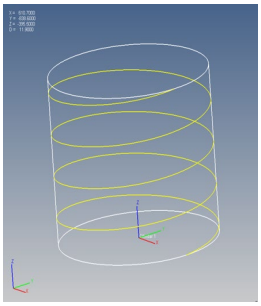


Fig. 3. *Spiral sampling strategy for cylindricity measurement*

The measurement strategy included the following parameters: scanning speed, number of points, diameter of the measuring probe tip, and the application of filters. The characteristics measured were cylindricity and center position. Measurements were performed along a spiral path at three different scanning speeds, and it was carried out both with and without filter application. In experiments where the measured data were filtered, a low-pass Gaussian filter with cutoff wavelengths of λc = 0.8 and λc = 8 was used. The least squares method was used for fitting the substitute geometry, and measurements were performed with three different probe tip diameters. The number of sampled points was also varied at three levels. Figure 4 shows the sampling of measuring points with probe tips of 1 mm and 5 mm diameter.

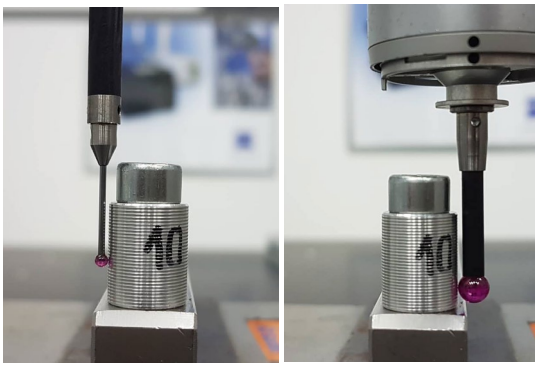


Fig. 4. *Measurement point sampling using 1 mm and 5 mm probe tips*

The Box-Behnken experimental design was used to create the experimental plan. This design was chosen for its efficiency, as it requires fewer experiments for the same number of input factors compared to the central composite design. Another reason for using the Box-Behnken design is the inability to set input parameters at a higher number of levels (Antony, 2014; Myers et al., 2016). Input factors were varied at three levels, with equal intervals between the levels. Input parameters and their levels are listed in Table 1.

Table 1. *- Input factors and their level values*

Input Factors	**Factor Level Values**		
	-1	0	1
Scanning speed - A	10	55	100
Number of points - B	25	75	125
Measuring probe tip diameter - C	1	3	5
Filter - D	no filter; 8	cut off 0.8;	cut off

Software Tools

The choice of software tools for data analysis is crucial, especially in cases where experiments and analyses involve multiple interdependent and influential variables (Kozhanov et al., 2019). In simpler analyses, differences in output results obtained using different software packages may be minimal or negligible. However, in more complex research settings, where multiple factors, interactions, and statistical relationships are considered simultaneously, software becomes the final and potentially decisive link in the data processing chain. Different software tools apply various statistical methods, data fitting models, rounding approaches, outlier handling procedures, as well as criteria for determining the significance of results. These differences, although often technical in nature, can have a significant impact on the final interpretation of results, drawing conclusions, and hypothesis validation. Therefore, software choice is not only a technical issue but also a methodological

one, which must be carefully considered in any serious research relying on statistical analysis. As the number of variables increases and analyses become more complex, differences in algorithms, statistical models, and result interpretation implemented by various software tools can substantially influence the final conclusions.
For the statistical processing of measurement data, this study employed Minitab and JASP, two software tools with differing strengths, to explore how software choice may affect data analysis and interpretation. These software tools may use different approaches for outlier handling, hypothesis testing, selection of statistical tests, and result visualization. Minitab stands out for its ease of use and specialized tools for industrial applications, while JASP, as a free and open-source software package, provides transparent insight into statistical methods but may have limitations regarding the availability of advanced options and flexibility (Alagić, 2021).

Minitab

Minitab is an example of a statistical software package developed primarily to perform statistical analysis with a high degree of numerical accuracy (Alagić, 2021). It is commercial statistical software designed mainly for industrial statistics, Six Sigma methodology, and quality control. It features an easily used interface, powerful tools for regression analysis, ANOVA tests, control charts, and design of experiments (DoE) (Ahmad, 2019). Thanks to its ease of use, Minitab is particularly suitable for users in industrial environments, as it does not require deep statistical knowledge while providing reliable data analysis. This software requires a paid license, which can be a limitation for academic and research institutions. Additionally, although it covers a wide range of standard methods, it does not include some advanced techniques offered by other software, such as Bayesian statistics.

JASP

JASP is free, open-source software developed by the University of Amsterdam with the aim of making statistical analysis more accessible and transparent, especially in academic contexts. Unlike Minitab, JASP supports Bayesian statistics, which makes it suitable for modern approaches to data analysis (van den Bergh et al., 2023; Love et al., 2019; Kelter, 2020). One of the key advantages of this software is its ability to automatically generate easy-to-read tables, charts, and analysis results, thereby significantly saving time in data processing (JASP Verification Project, 2023). JASP supports commonly used statistical methods such as t-tests, ANOVA, regression analysis, factor analysis, and correlations. However, JASP has a limited selection of methods for advanced analyses such as nonlinear regressions, structural models, and similar techniques. Additionally, JASP exhibits lower stability and longer processing times when handling large datasets, and it has certain limitations in flexibility regarding script implementation and automation of the analysis process.

Criteria for Comparative Analysis

In order to conduct a relevant comparative analysis, based on practical work with the software as well as insights from available literature, criteria were defined that include various aspects of their functionality, availability, and applicability. The analysis is based on the following criteria:

- Licensing and availability,
- Selection of statistical methods,
- User interface and accessibility,
- Data visualization,
- Flexibility of the software package.

Based on these criteria, a comparative analysis of both software packages will be presented below, with particular emphasis on their advantages and limitations in the context of application in experimental research and measurement data processing.

RESULTS AND DISCUSSION

This chapter presents and analyzes the results of statistical data processing obtained from the previously described measurements. The primary goal of the analysis is to examine the extent to which the choice of statistical software affects the interpretation of measurement results, as well as to identify potential differences in data presentation, processing, and interpretation (Wake et al., 2022). Analysis includes specific statistical methods and visualizations, such as regression analysis, residual analysis, scatter plots, Q-Q plots, and response surface diagrams.
Experiment was conducted following the Box-Behnken design, with a total of 45 measurements performed for each workpiece, covering different combinations of input factor levels. During each measurement, the cylindricity, as well as the X and Y coordinates of the workpiece center, were recorded.
Initial analysis of the results was conducted using Minitab 17, focusing on basic statistics and graphical presentations to identify potential patterns, deviations, and the influence of input parameters. Subsequently, the data were also analyzed with JASP software to enable comparison and derive fundamental statistical conclusions.

Deviation Analysis of Cylindricity

Figure 5 shows boxplot diagrams of cylindricity deviation for eleven workpieces, obtained using different software tools. The purpose of the presentation is to identify differences in the distribution of measurement data and to assess the impact of the software on the output results.
Similar distribution trend was observed in both software tools; the lowest median deviation value was identified for cylinder 1, cylinder with the finest surface finish, while the largest deviation was observed for cylinder 11, cylinder with the roughest surface. In both software packages, results indicate that increased surface roughness contributes to greater deviation from geometric tolerance. Therefore, in both cases, pronounced variability of results is visible for the cylinder with the rough surface, while data for cylinders with fine surfaces are significantly more stable. Such analysis is useful for assessing the impact of surface finish quality on measurement results, and the software tool that provides clearer and more informative visualization can play a decisive role in analyzing results and drawing conclusions.

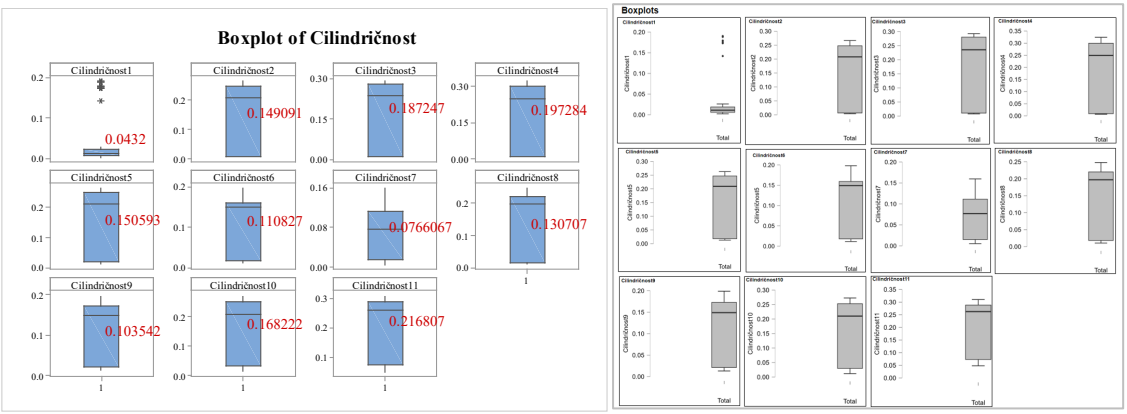


Fig. 5. *Boxplot diagram of cylindricity deviation – Minitab vs. JASP*

Visual presentations in software differ in the way of interpretation:

- Minitab provides additional information through numerical labeling of mean values directly on the diagram.
- JASP displays mean values in the tabular section, but not on the diagram itself.
- Clear depiction of isolated values (e.g., cylinder 1) is present in both software packages.
- JASP shows unique scales for each diagram, while Minitab often uses graphs with the same scale for all diagrams.

In this specific case, Minitab proved to be more suitable for visual analysis and comparison of all workpieces due to its built-in features that automatically display mean values and use a unified scale across all workpieces, which facilitates comparison. However, if a specific analysis of an individual workpiece were desired, JASP would be more appropriate.

Analysis of center position deviation

Based on the statistical analysis conducted and the results shown in Figure 6, the measured values of the center coordinates of the workpieces fall within approximately the same range, exhibiting similar deviations. This indicates that choice of software did not affect the actual output results, but only the way they were visually interpreted.

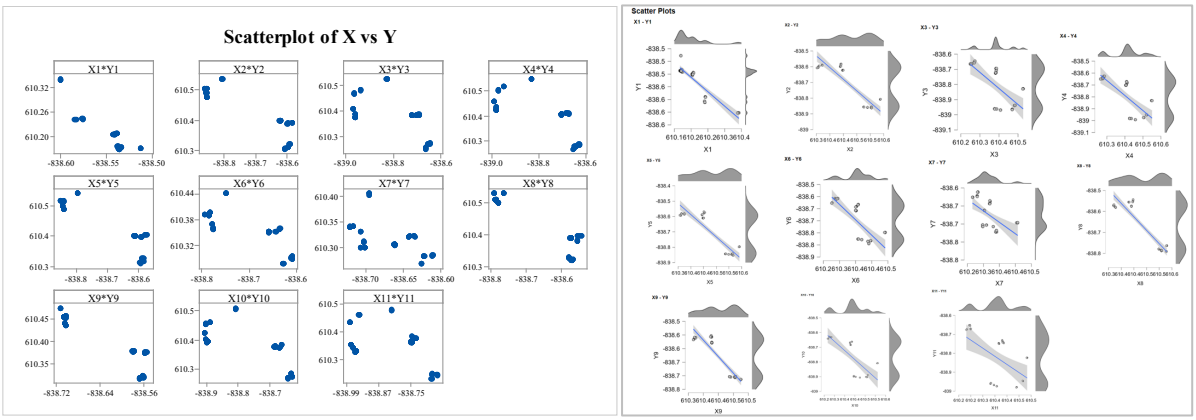


Fig. 6. *Centre position deviation – Minitab vs. JASP*

Visual presentation of data highlighted the following differences between the software:

- Minitab provides a Scatter plot display for all samples through a quick and clear visualization; however, the graphical output automatically generated by Minitab is less detailed. In addition to this basic view, Minitab allows enabling additional options for more detailed visualization.
- JASP displays individual Scatter plots with added regression lines and confidence intervals, giving a clearer picture of the strength of relationships between variables. The displays are more detailed and automatically generated, but the relationships are created and viewed individually.

Therefore, visualization generated in Minitab is suitable in cases where the goal is to present the overall relationship between variables, that is, the general structure of the data and overall correlations. However, JASP is more appropriate when a more detailed analysis of individual relationships is required, allowing for in-depth examination of the connections between specific variables.

Analysis of Results for Cylinder 1

To ensure a more concise presentation of results, this paper presents analysis for only one representative cylinder. Cylinder 1 was selected as the sample for result presentation due to its specific characteristics related to surface machining. This workpiece has the lowest arithmetic average roughness value, was finished using fine grinding, and has a surface quality grade of N5. For this reason, it is the most difficult to detect deviations and assess the influence of input factors on output characteristics. Cylinders with rougher surfaces exhibit greater deviations and wider variations in the output results. To further highlight the influence of surface roughness and machining method on the output results, this section concludes with 3D response surface diagrams for both the smoothest and the roughest cylinders. Since JASP does not directly support the generation of these diagrams, they were created using Minitab, thereby also illustrating the capabilities and limitations of both software tools in the context of this specific analysis.

Residual Analysis

To assess the accuracy of the model and identify deviations from expected values, a residual analysis was performed (Fox, 2015; Hand, 2014). This step is essential for validating the model and detecting potential imperfections. Residuals represent the differences between the actual measured values and the values predicted by the model. Figure 7 shows results of residual analysis in both software tools.

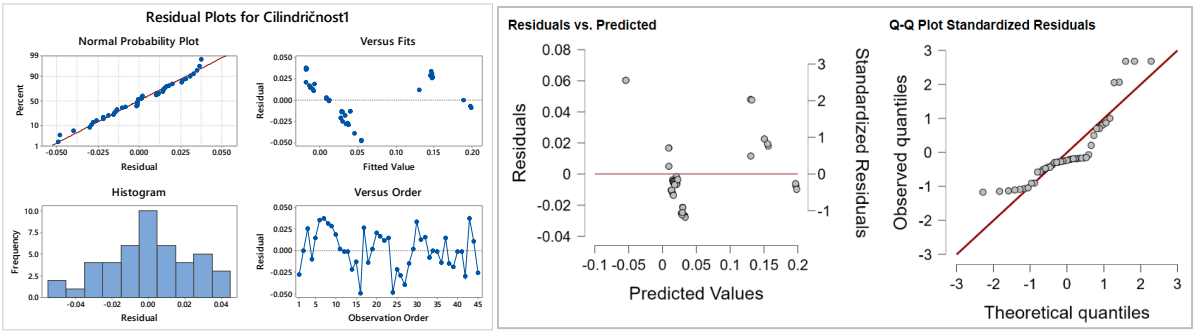


Fig. 7. *Residual analysis for Cylinder 1 – Minitab vs. JASP*

Residual analysis results indicate consistent conclusions across both software tools. The normal probability plot in Minitab shows that most of the observed values follow the expected line of normal distribution, with minor deviations at the tails of the plot, i.e., in the extreme values. A similar conclusion is supported by the Q-Q plot in JASP, where the standardized residuals largely follow the theoretical distribution line, with slight deviations at the ends. Based on this, it can be concluded that the residuals are approximately normally distributed, which confirms the validity of the applied model.

The residual histogram in Minitab further emphasizes the nearly symmetric distribution of values. The analysis in both software tools shows that most residuals fluctuate around zero, without a noticeable systematic trend, although some individual local deviations are evident. These deviations may indicate the influence of specific measurement points or machining processes.

One advantage of Minitab is its ability to display residuals in relation to the order of measurement, allowing the observation of fluctuations without a clear trend that would indicate a process error. JASP, however, offers a simpler and cleaner standardized residual plot, making it easier to detect deviations from expected values.

Overall, the results obtained in the software packages are largely consistent. Both software tools confirm that the model adequately describes the process, with Minitab allowing more

detailed analysis through a greater number of graphical outputs. Conversely, JASP provides clearer and more accessible visualizations of standardized deviations. It can be concluded that both software packages validate the reliability of the obtained results, with differing strengths in terms of visualization and analytical detail.

Analysis of the Influence of Input Parameters on Measurement Results

In this analysis, influence of four key input factors on the measurement results was examined: scanning speed, filter application, probe tip diameter, and number of points. Understanding the impact of these parameters on the output results is crucial for optimizing the measurement process and the accuracy of the obtained data. The effects of each parameter were analyzed, allowing for the identification of potential areas for improvement in the measurement process.

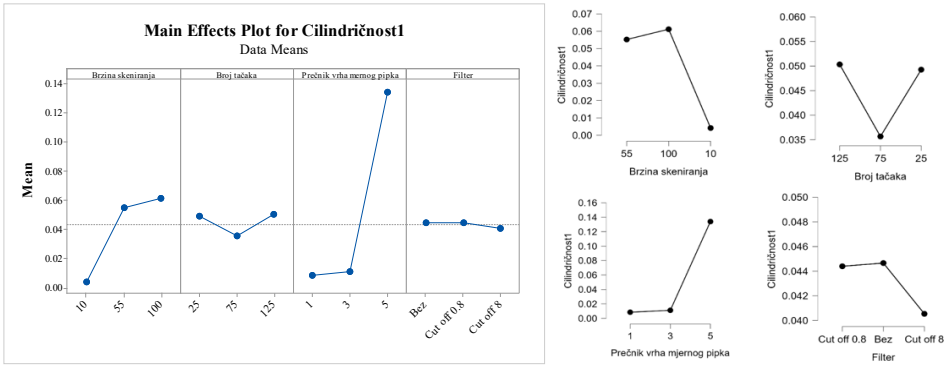


Fig. 8. *Main Effects – Minitab vs. JASP*

In Minitab, as shown in Figure 8, all main effects are presented in a single combined plot, allowing for direct comparison. Diagram indicates a pronounced influence of the probe tip diameter and scanning speed on the cylindricity tolerance. The cylindricity deviation significantly increases when using the largest probe tip diameter and the lowest scanning speed. Other factors, such as the number of points and filtering, show less significant effects. In JASP, as shown in the same picture, each factor is presented in an individual plot, which allows for better clarity when analyzing the influence of each factor separately. Observed trends are fully consistent with the results from Minitab, the cylindricity deviation increases with use of larger probe tip diameters, and greater deviation is also recorded at the lowest scanning speed. The lowest cylindricity deviation was achieved by applying a filter with a cutoff wavelength of λc = 8, while the number of points shows minimal influence, with a slight effect observed at the medium point count. Analysis identified the most dominant factors, probe tip diameter and scanning speed, leading to a more detailed analysis of their effects in the following subsection. Results obtained in both software packages are consistent, with the main difference being in the format of the visualization. Minitab allows for complete visualization of all factors and easier comparison between them, while JASP offers a more detailed display of each individual variable, which can be useful for analyzing specific effects.

3D Response Surface Plot

Response surface plots were generated to visually present the relationship between input factors and the output characteristics of the processing operation. The use of 3D visualization allows for easier observation of interactions between variables and identification of regions where optimal results are achieved (Feng et al., 2007). For the analysis, two representative samples were selected: Cylinder 1, with the finest surface finish, and Cylinder 11, with the roughest. The comparative presentation of the plots provides insight into how surface quality and changes in input factors affect the sensitivity of output parameters.

As previously noted, JASP lacks support for DoE and advanced modeling, which includes 3D response surface generation. This is consistent with previous findings indicating that, while JASP is user-friendly and transparent, its functionality remains partially limited when it comes to complex statistical methods (Love et al., 2019). Minitab is also quite a closed system regarding the analysis of data beyond the standard framework, so its use can sometimes be limited when working with non-standard data formats because it does not always allow extensibility and full control over the analysis. Similar observations regarding the advantages and limitations of statistical software tools in quality control have been noted in comparative studies of other platforms as well (Kozhanov et al., 2019).

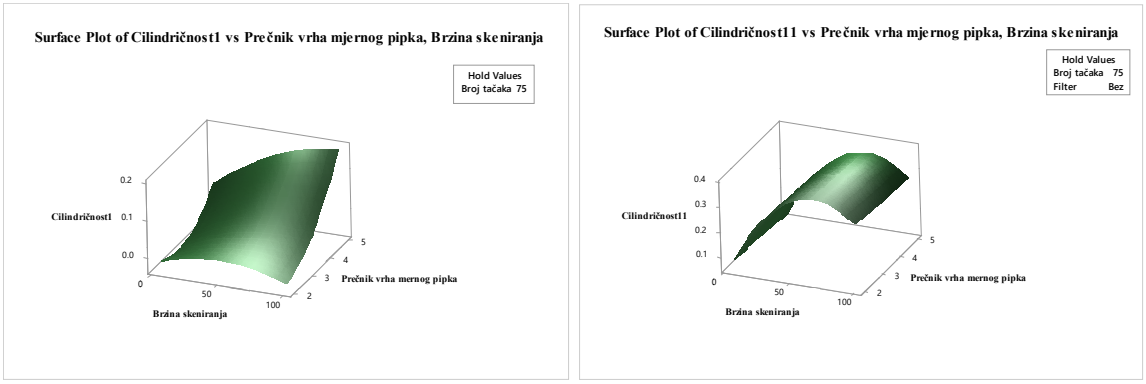


Fig. 9. *Response surface plot – Cylinder 1 vs. Cylinder 11*

In the case of Cylinder 1, the response surface shows a relatively flat trend, indicating lower sensitivity of the measurement process to changes in input parameters. The highest level of cylindricity deviation is observed at the combination of low scanning speed and large probe tip diameter, while at higher speeds and smaller diameters, the results appear more stable. These results are justified considering the more precise surface treatment method used.
For Cylinder 11, the response surface plot shows a more pronounced curvature, with higher values of cylindricity deviation and greater variability in relation to the same factors. The response surface also indicates greater system sensitivity to changes in input parameters, which aligns with the nature of rough machining such as turning. This highlights the need for more precise control of measurement parameters when assessing dimensional accuracy for such processed surfaces. While grinding results in more stable geometric accuracy and less sensitivity to measurement, rough turning exhibits greater variation requiring additional metrological attention.

CONCLUSION

This study presents a comprehensive comparison of statistical results from measurements of cylindricity deviation and center coordinates of workpieces, aiming to evaluate how the choice of software influences the interpretation of measurement data and the drawn conclusions. The results indicate that the choice of software did not affect the actual output values; key statistical results and trends showed consistency regardless of the software used. However, the manner of visual presentation, available functionalities, and the flexibility of the software environment significantly influence the analysis workflow and result interpretation. JASP does not directly support the creation of response surface models, which can be crucial for process optimization in engineering applications. Additionally, this software offers limited support for Design of Experiments (DoE), which is a significant drawback in technical research. Due to these limitations, JASP was primarily used in this work for enhanced visualization in specific areas of statistical processing, while advanced experimental modeling and analysis methods were conducted using Minitab. Otherwise, especially in the early stages of research, JASP can be more accessible in terms of usability, as it is visually adapted, accessible, and unlike Minitab, provides automatic generation of detailed analyses of individual effects through separate graphs.

In conclusion, analysis has shown that Minitab and JASP differ significantly in terms of accessibility, available features, and suitability for specific types of statistical tasks. JASP as free and open-source tool makes it more accessible for students and researchers. Its clear interface and ease of use support quick execution of basic statistical analyses and visualizations. However, its capabilities are limited when it comes to more advanced procedures, such as experimental design and response surface modeling, which reduces its usefulness in engineering contexts. Minitab, by contrast, includes a broader range of tools designed for more complex analyses. It supports experimental design, advanced visualization of residuals, and modeling of multi-factor systems, which makes it better suited for industrial and technical applications. Still, its closed system and higher learning curve can pose challenges, especially when dealing with unusual data formats or when more flexibility is needed in data handling. The comparison suggests that the choice between these programs should be guided by the specific goals of the analysis, the complexity of the data, and the user's level of experience. The combination of both tools can significantly enhance the quality of the analysis and decision-making. The combined use of both software tools in this study achieved a balance between complexity, clarity and individual analytical detail. JASP provided a basic and visually clear analysis, while Minitab enabled the execution of more advanced statistical procedures and process modeling.

Future research should include expanding the analysis through additional software tools (e.g., R, Python) to achieve greater flexibility, extensibility, and potential integration of machine learning methods.

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