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COMPARATIVE ANALYSIS OF STABILITY AND CAPABILITY OF TWO DRILLING PROCESSES IN THE CAST PRODUCT USING SPC TOOLS

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Abstract: This article presents the results of comparative studies of the machining processes of holes B and C, conducted under batch production conditions at a foundry enterprise. The analyzed qualitative characteristic was the hole diameter, which is a key dimensional parameter of the tested casting product. The aim of the study was to evaluate both drilling processes using Statistical Process Control (SPC) tools to identify the superior process in terms of stability over time and quality capability. The methodology included descriptive statistics, histogram and box plot analysis, Bland-Altman agreement testing, normality verification, and Johnson-transformed control charts. Capability indices (Cp, Cpk) and target-oriented indices (Cpm, Cpmk) were calculated using the Clements percentile method to ensure reliable interpretation for non-normal data. The results confirmed that both processes were statistically stable and demonstrated very high capability, with Cp and Cpk values exceeding 2.0, thus indicating a negligible risk of producing out-of-tolerance parts. Nonetheless, important differences were observed: process B showed lower short-term variability, nearly perfect centering within the tolerance field, and stronger capability toward the lower specification limit. In contrast, Process C, although characterized by slightly higher variability, achieved closer alignment with the nominal dimension and more balanced capability across tolerance limits, as reflected in its higher Cpm and Cpmk values. These findings highlight the need to combine stability, capability, and accuracy-to-target analyses to obtain a comprehensive picture of process quality performance, especially under conditions of asymmetric specification limits and non-normal data. From a practical perspective, both processes are stable and capable, suitable for further batch production. However, Process C can be considered generally superior due to its better alignment with the nominal value and greater actual process capability, which translates into a lower risk of producing out-of-spec products.

Keywords: foundry engineering, Statistical Process Control (SPC), control charts, process stability analysis, process capability analysis, comparative analysis

1. INTRODUCTION

Every manufacturing company strives to achieve ideal manufacturing processes. An ideal process, from both a process and product evaluation perspective, is one that is statistically

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stable – free from special causes and predictable over time – and simultaneously qualitatively capable, ensuring that all products are maintained within tolerance and meet the client's requirements (Wheleer, 2000). The consequence and benefit of an ideal process is ensuring stable product quality while simultaneously reducing costs, reducing the risk of defects, and increasing predictability and production efficiency (Hamrol, 2018; Brook, 2010; Breyfogle, 2003). In manufacturing production, ensuring process stability and capability is a prerequisite for maintaining product quality and, ultimately, customer satisfaction (Wheeler and Chambers, 1992; Knop, 2021). Product and process quality is a dynamic and complex concept (Czajkowska and Ingaldi, 2021; Czajkowska and Ingaldi, 2022), therefore it is necessary to constantly verify the level of their fulfillment.

To obtain a complete picture of process performance, statistical process control (SPC) tools such as control charts are used to assess process stability and predictability over time, and capability indices (Cp, Cpk, and related) are used to verify the process's ability to maintain results within tolerance limits (Montgomery, 2019). SPC is a set of statistical methods and tools for monitoring, analyzing, and improving production processes by measuring and controlling their variability (Montgomery, 2019; Ryan, 2011; Knop, 2023). The goal of SPC is to detect and eliminate the causes of so-called special variation, i.e., assignable cause variation, and then ensure the process's stability and ability to meet quality requirements (Oakland and Oakland, 2018). SPC provides a framework for monitoring process behavior, detecting abnormal variability, and supporting continuous improvement initiatives (Zontec Press, 2010).

In SPC, it is crucial to understand whether the process is statistically behaving normally, i.e., according to a normal distribution, or "abnormally," exhibiting deviations from the classic Gaussian curve (asymmetry, flattening, or excessive concentration of values) (Montgomery, 2019). This determines the selection of appropriate SPC analysis tools (Wheeler, 2004). For processes whose results are distributed according to a normal distribution, classic control charts and capability indices are sufficient, while for non-normal processes, data transformation methods or percentile-based indices are necessary to ensure reliable and credible assessment of stability and capability (Montgomery, 2019, Kotz and Johnson, 1993; Pearn et al., 1992).

Machining processes play a key role in the production of metal components, where dimensional accuracy and repeatability directly determine the functionality and reliability of the final product (Okokpujie et al., 2019). In the foundry industry, where cast parts often require finishing to meet dimensional specifications, assessing the stability and capability of machining processes provides valuable information about potential or real problems with the process or product, or confirms the absence of hazards, which provides important support in management decisions regarding the control and improvement of the production process (ISO 22514-2, 2017; Ignaszak and Sika, 2012; Leby and Knop, 2025).

The aim of the study was to comparatively evaluate the stability and capability of the B and C hole drilling processes in the tested foundry product under batch production conditions, taking into account the specificity of actual measurement data, which do not meet the assumptions of a normal distribution. Hole diameter was analyzed as a key quality characteristic, determining the product's functionality. The aim of the study was to assess process stability using control charts and to evaluate the process capability in order to compare the two processes and determine which one is superior in terms of both process evaluation criteria.

The added value of this study lies in the use of comprehensive SPC analysis for non-normally distributed data, which allowed for a more reliable comparison of two parallel machining processes for identical product characteristics, thus identifying differences in process stability and capability assessments that were not visible with classical SPC procedures.

2. RESEARCH METHODOLODGY

The research object is a foundry manufacturing company specializing in large-scale production of metal components. Manufacturing processes related to hole machining were analyzed. The analysis involved two machining (drilling) processes performed on the same cast product, for a dimensional characteristic of 2× Ø6.02 mm with a tolerance of +0.04/−0.02 mm. Because the product contained two holes with identical specifications (B and C), each hole was treated as a separate quality characteristic. The goal was to compare the stability over time and the capability of both processes to meet the specification limits (LSL, USL) and the target (NOM). Measurements were performed using a coordinate measuring machine (CMM) according to the control plan. Data were recorded in chronological order. For each characteristic, fixed subgroups were used, with a size n resulting from the control plan ($n = 4$). Before statistical analysis, the adequacy of the measurement system (CMM) was assumed.

In the first stage, an analysis of basic statistical measures was carried out for each series (B and C). The following statistical measures were determined: mean, median, mode, standard deviation, coefficient of variation, min-max, range, quartiles (Q1, Q3), skewness, and kurtosis (Kiemele et al., 2005). Relation between the mean values and standard deviations was showed by Mean ± SD plot. The shape of the distribution was assessed using a histogram and box plot. The Bland-Altman method was used to assess the agreement between the two analyzed drilling processes (Hole B and Hole C). This method is widely used to compare two measurement methods because it allows for the quantitative assessment of both the systematic deviation (bias) and the determination of the limits of agreement within which 95% of the observed differences lie (Bland and Altman, 1986; Doğan, 2018; Giavarina, 2015). By applying this analysis, it was possible to verify whether both processes can be considered equivalent and interchangeable from the point of view of the analyzed dimensional quality characteristics. The normality of the distribution was tested using normality plots and the normality tests (Shapiro-Wilk, Anderson-Darling, et al.). Normality tests revealed deviations from the normal distribution. Therefore, classical methods for assessing process stability and capability based on normality were abandoned in favor of fitting non-normal distributions.

The stability of processes B and C was assessed using X-bar control chart constructed from Johnson-transformed data. The analysis included verification of the presence of points outside the control limits and signals indicating the presence of special.

Process capability was assessed using the indices Cp, Cpk, CPL, CPU, and the centering index K, using fitted Johnson and Pearson distributions. The indices were calculated using the Clements percentile method (Ahmad et al., 2007), which does not require the assumption of normal distribution and allows for a reliable interpretation of the capability of non-normal processes. Additionally, the results were compared with calculations based on the classical assumption of normality to highlight differences.

In the final stage of the analysis, additional capability indices of the Cpm family (Cpm, CpmL, CpmU, and Cpmk) were calculated in order to account for both process variability

and deviations of the mean from the nominal specification value (Chang et al., 1988). These indices were determined using the Clements percentile method, which replaces the classical within-sample standard deviation with a percentile-based equivalent of six sigma, derived from the 0.135th and 99.865th percentiles of the sample distribution (Clements, 1989).
In the final step, the results obtained for processes B and C were compared by analyzing their stability, capability, and centering relative to the nominal specification, which enabled the identification of the process that demonstrated superior dimensional quality.
All graphs and calculations were performed in TIBCO Statistica 14 software (descriptive statistics, shape of distributions, normality plots, control charts, capability indices) and PQStat 1.8.2 (normality tests).

3. RESULTS AND DISCUSSION

3.1. Evaluation of basic statistical measures and the shape of the distribution of drilling processes B and C

Table 1 presents the results of calculating basic descriptive statistics for 124 data sets from processes B and C.

Table 1. Analysis of basic statistical measures for drilling processes B and C

Hole	Mean	Median	Mode	Minimum	Maximum	Lower Quartile	Upper Quartile	Range	Std.Dev.	Coef.Var.	Skewness	Kurtosis
B	6.030	6.030	6.031	6.022	6.040	6.026	6.033	0.018	0.0051	0.084	0.154	-0.943
C	6.029	6.030	6.031	6.020	6.039	6.024	6.032	0.019	0.0052	0.087	0.027	-1.015

Source: own study with the use of TIBCO Statistica 14.0

The mean results for both processes B and C are very similar (B: 6.030 mm; C: 6.029 mm), which – with similar medians – suggests a lack of significant asymmetry. Both processes were characterized by a slight right-sided skew, with process B exhibiting a slightly larger skew. The most common value in both processes was 6.031. The range of data variability was slightly greater for process C (R = 0.019). The standard deviation in both cases is similar (0.0051-0.0052 mm), and the CV does not exceed 0.09, indicating a small relative spread of the measurements around the mean. The kurtosis values of -0.943 and -1.015 indicate a platykurtic distribution, i.e., its flattening and a lower frequency of extreme values compared to a normal distribution. Since the kurtosis values for both processes B and C (-0.943 and -1.015) do not fall within the conventional range for the normal distribution (< -0.5; +0.5>), it can be concluded that the distribution of the examined data in both processes deviates from normality
Figure 1 shows a comparison of the mean value and standard deviation (mean ± SD) for the B and C hole diameter data sets.

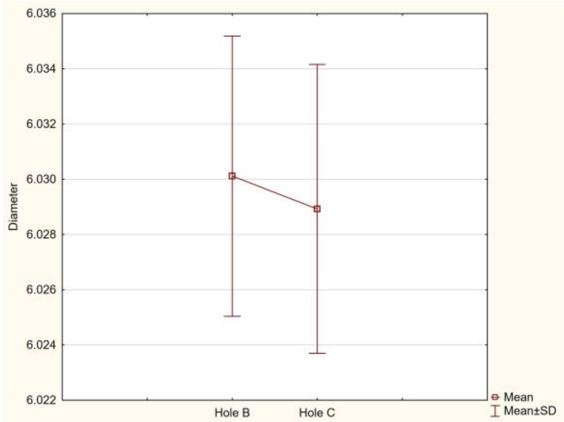

Fig. 1. Mean±SD of Hole B and C
Source: own study with the use of TIBCO Statistica 14.0

The analysis shows that the mean dimension value for hole B is approximately 6.030 mm, while for hole C it is slightly lower at 6.029 mm. The difference between the mean values of both holes is therefore marginal (on the order of 0.001 mm). The standard deviations for both cases are comparable, approximately ±0.005 mm around the mean, indicating high repeatability of both processes. The ranges of variation (Mean±SD) in both processes fully overlap, suggesting no statistically significant differences between the dimensions of holes B and C.
Figure 2 shows histograms with fitted normal density curves for holes B and C.

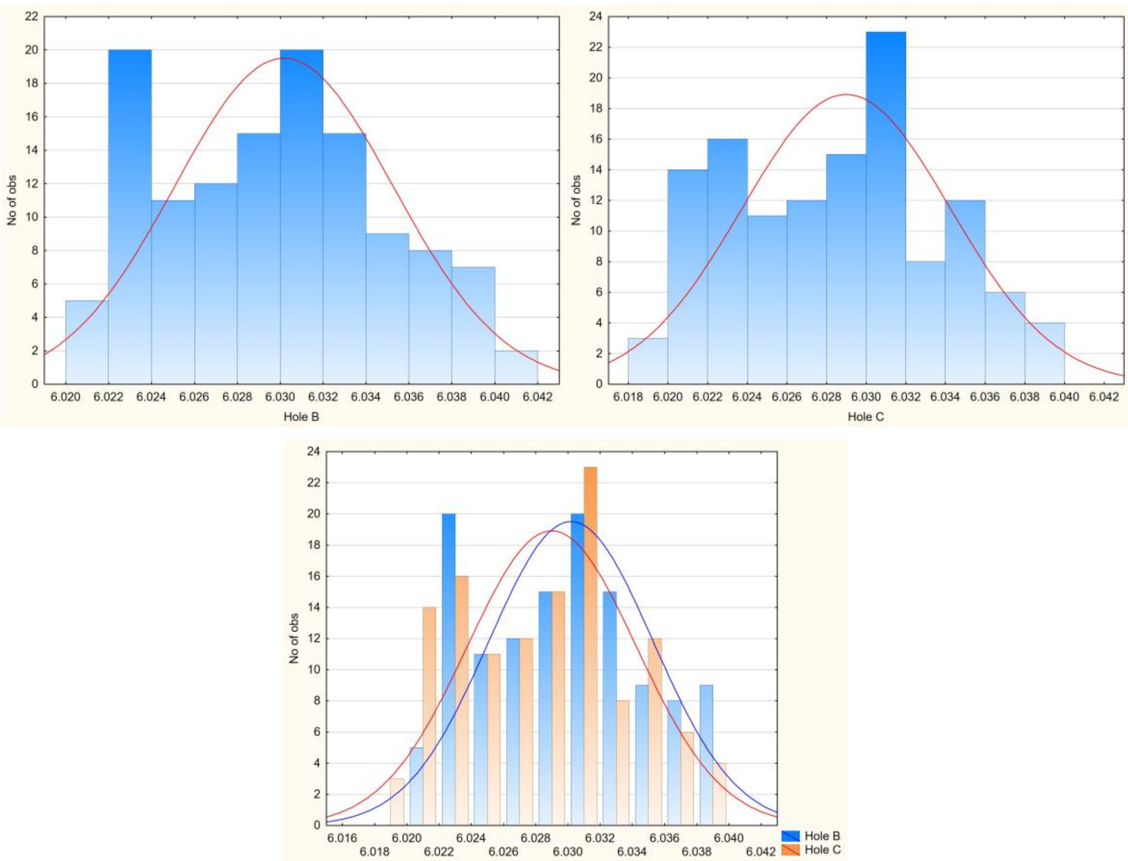

Fig. 2. Independent histogram of Hole B and Hole C and side-by-side histograms of Hole B and C
Source: own study with the use of TIBCO Statistica 14.0

The distributions of results for both processes are similar and center around 6.030 mm, slightly larger than the nominal (NOM) value of 6.020 mm. For hole C, the distribution is characterized by a slightly larger spread of measured values, while hole B is characterized by a slightly more concentrated distribution around the mean value. The shape of both histograms indicates multimodality of the results from both processes.
Figure 3 shows a comparative box plot for hole dimensions B and C.

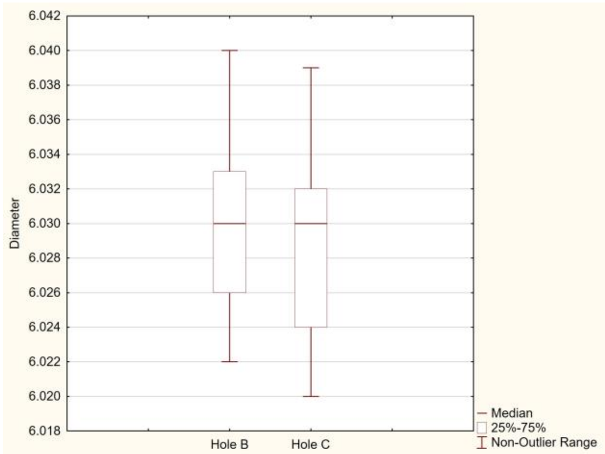

Fig. 3. Side-by-side boxplots of Hole B and C
Source: own study with the use of TIBCO Statistica 14.0

The medians of both processes are identical at 6.030 mm. This value indicates that half of the measured elements in these processes have dimensions less than 6.030 mm, while the other half have dimensions greater than 6.030 mm. The entire measurement range falls within the ranges of 6.022-6.040 mm for hole B and 6.020-6.039 mm for hole C, respectively. Both processes are characterized by a right-sided skewness, which is slightly greater for process B. The interquartile range (IQR) showing the variability with respect to the middle 50% values (Q3-Q1) of the data set is slightly larger for process C (0.008) than for process B (0.007).
With respect to the nominal dimension NOM = 6.020 mm and a tolerance of +0.040/-0.020 mm (permissible range 6.000-6.060 mm), all measured values in both processes are within the tolerance limits. Both processes are skewed towards values greater than NOM.
In order to assess the agreement between the two drilling processes (Hole B and Hole C), the Bland-Altman method was applied (Fig. 4). This approach enables the evaluation of systematic bias between the processes as well as the limits of agreement for paired measurements (Doğan, 2018). The method was therefore selected to verify whether the results obtained from processes B and C can be considered equivalent in terms of the dimensional quality characteristic under investigation.
The Bland-Altman analysis of 124 paired measurements revealed a negligible mean bias between Hole B and Hole C (-0.0012 mm), with Hole C tending to produce slightly smaller diameters. The 95% limits of agreement (-0.0159 mm to +0.0136 mm) show that, in 95% of cases, the differences between Hole B and Hole C remain within ±16 μm. This indicates that the two drilling processes yield highly consistent and practically interchangeable results. The overall width of the agreement interval, which shows the total range within which 95% of the differences between holes B and C fall, is 0.02947 mm (29.5 μm), which

is less than half the specified tolerance band (0.060 mm). This confirms the high agreement and practically interchangeable nature of the two processes.

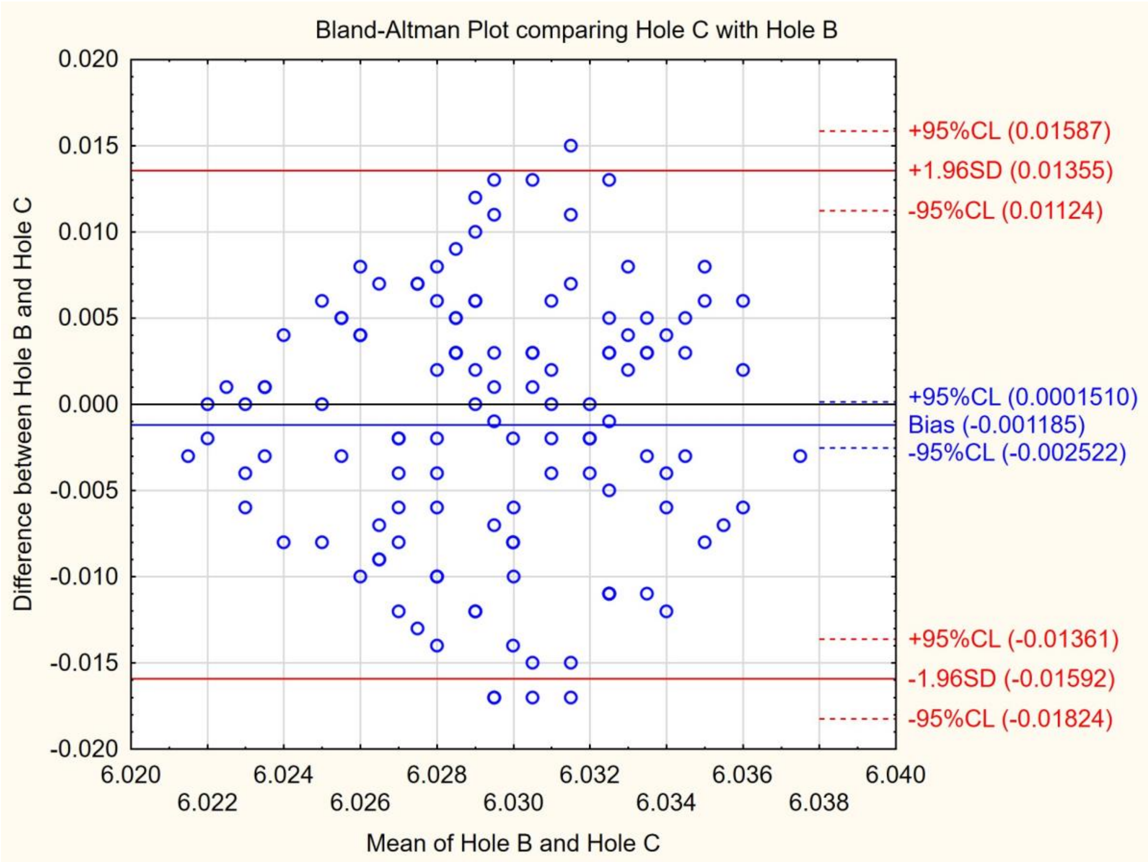

Fig. 4. Bland-Altman plot of agreement between drilling processes B and C for hole diameter measurements

Source: own study with the use of TIBCO Statistica 14.0

The Figure 5 shows normal probability plots for the data relating to the dimensions of holes B and C.

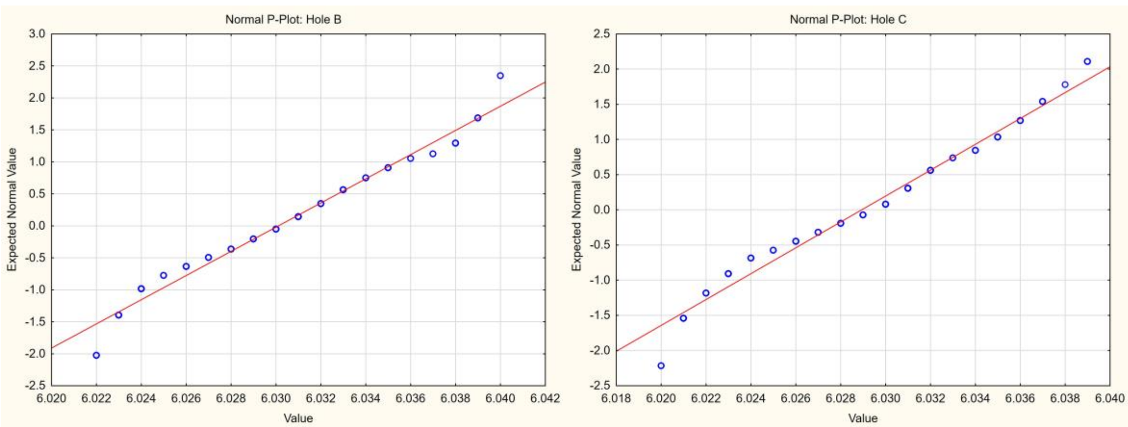

Fig. 5. Probability plots of Hole B and C

Source: own study with the use of TIBCO Statistica 14.0

If the observed values (plotted on the x-axis) are normally distributed, all values should fall on a straight line on the graph. If the values are not normally distributed, they will deviate from the straight line (Montgomery, 2019). The normality plots for both processes show some disturbances in the data distribution relative to the normal distribution, visible in the tails of the distribution, which may result from the greater "heaviness" of the tails compared to the normal distribution for both processes. The normality plots showed a general lack of fit and a characteristic S-shaped pattern around the lines, indicating that the analyzed processes will require transformation before applying the normality procedure. To further confirm that the processes deviate from the normal distribution, normality tests were applied.
The results of various normality tests of the distribution of data sets for processes B and C are presented in Table 2.

Table 2. Normality analysis of the data sets for Hole B and C

Analysed variables	**Hole B**	**Hole C**
Group size	124	124
Number of unspecified	0	0
Number of missing data	0	0
Significance level	0.05	0.05
Group mean	6.030113	6.028927
Group standard deviation	0.005072	0.005232
Kolmogorov-Smirnov test		
D statistic	0.087547	0.097204
Degrees of freedom	124	124
p-value	0.281222	0.1797
Lilliefors test		
D statistic	0.087547	0.097204
Degrees of freedom	124	124
p-value	0.020779	0.005883
Shapiro-Wilk test		
W statistic	0.956777	0.96052
Z statistic	3.261178	3.05794
p-value	0.000555	0.001114
D'Agostino-Pearson test		
K-square statistic	15.667295	20.448646
Degrees of freedom	2	2
p-value	0.000396	0.000036
Skewness test		
Skewness	0.153753	0.026897
Z statistic	0.72379	0.127208
p-value	0.469195	0.898776
Kurtosis test (g2)		
Kurtosis	-0.943211	-1.014724
Z statistic	-3.891455	-4.520228
p-value	0.0001	0.000006

Source: own study with the use of PQStat 1.8.2

Normality tests indicate rejection of the normality hypothesis for both B and C holes (Shapiro-Wilk: $p < 0.05$; D’Agostino-Pearson: $p < 0.05$). At the same time, no clear

asymmetry is observed, but kurtosis deviates from zero (leptokurtosis), which indicates thicker tails than in the normal distribution.
Analysis of the distribution shapes for holes B and C revealed deviations from normality, which limits the applicability of classic Shewhart control charts and capability indices based on the normal distribution. To ensure a reliable assessment of process stability and capability, the data were transformed according to the Johnson distribution family. Fitting appropriate Johnson curves transformed the data into a form close to a normal distribution, enabling reliable control chart analysis results and reliable values of process capability indices (Cp, Cpk) (Kane, 1986).

3.2. Assessment of the stability of drilling processes B and C over time

Figure 6 presents the Non-Normal X-bar and Range control chart for Hole B, where a Johnson transformation was applied to fit the data to a normal distribution.

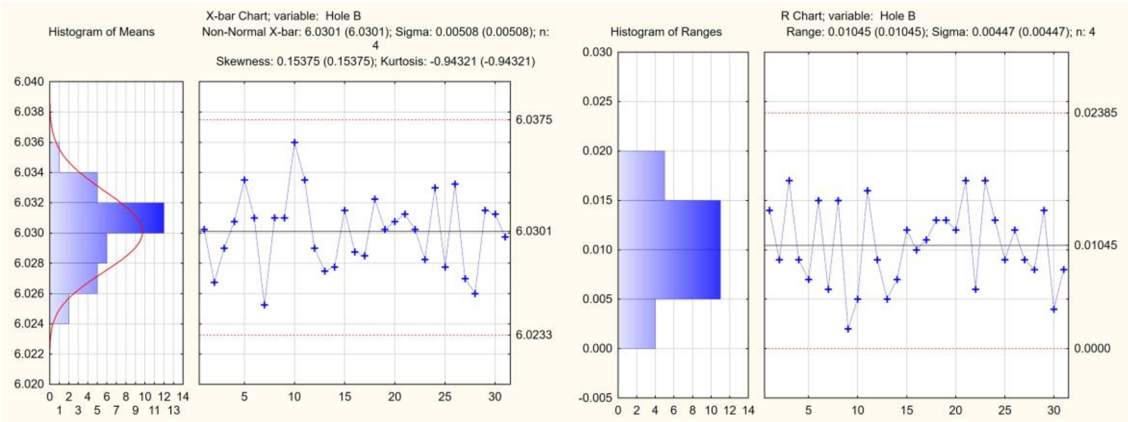

Fig. 6. Non-Normal Xbar and Range chart for Hole B
Source: own study with the use of TIBCO Statistica 14.0

The control chart for process B showed no points exceeding the control limits, and the dispersion of measurements remained within them, indicating process stability. The run tests performed for the Xbar and R charts did not show any specific patterns of points indicating a potential deregulation of process B.
Figure 7 shows the Non-Normal X-bar and Range control chart for Hole C.

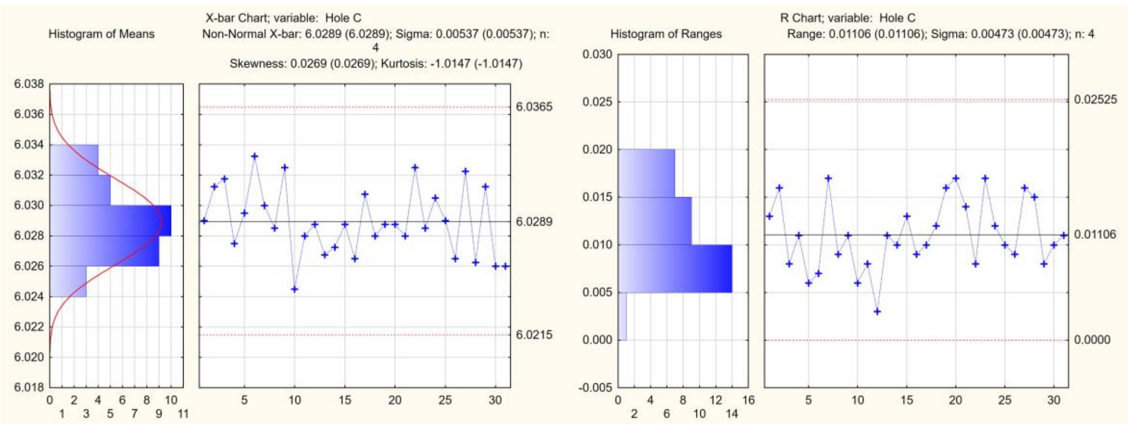

Fig. 7. Non-Normal Xbar and Range chart for Hole C
Source: own study with the use of TIBCO Statistica 14.0

The control charts for process C showed that all points were within the control limits, confirming the statistical stability of this process. No specific patterns of points were observed on the control charts using test runs, indicating the absence of signals indicating the presence of special causes..
Both processes B and C can be considered statistically stable, as no points outside the control limits or stability violations were observed on the X-bar charts. Nevertheless, process B exhibits a slightly higher level of stability compared to process C. After the Johnson transformation, the estimated standard deviation for process B is approximately 0.00508, while for process C it is approximately 0.00537. This means that the short-term variability of process B is approximately 6% lower than that of process C. The X-bar chart for process C also shows a larger amplitude of fluctuations in the mean values around the center line. In process B, the dispersion of the means is slightly more concentrated. Overall, process B can be considered slightly more stable and consistent over time.

3.3. Assessment of the quality capability of drilling processes B and C

The Figure 8 shows the analysis of the drilling process capability of Hole B, taking into account the non-normal distribution fitting (method of moments).

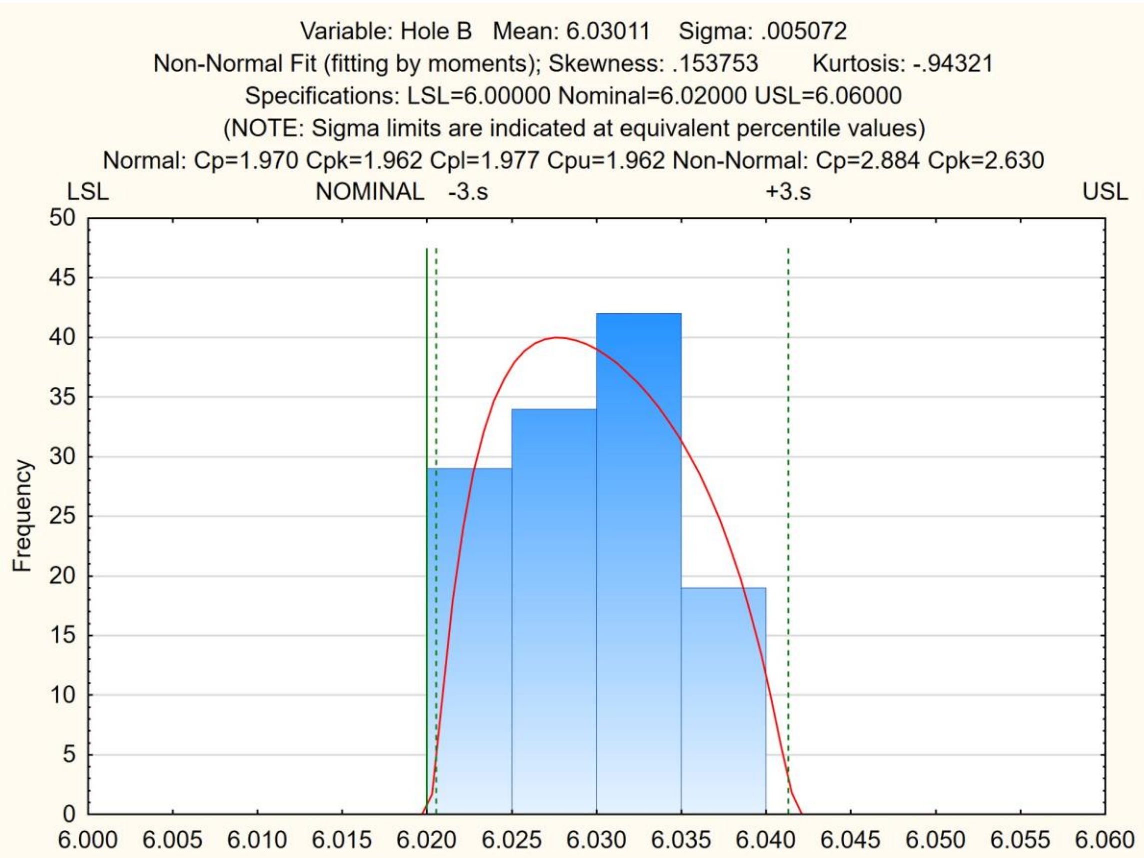

Fig. 8. Non-Normal Capability analysis for Hole B
Source: own study with the use of TIBCO Statistica 14.0

The capability indices calculated using the normal distribution assumption are Cp = 1.970 and Cpk = 1.962, suggesting that the process meets quality requirements very well and is

well centered within the tolerance zone (LSL = 6.000 mm; USL = 6.060 mm). However, analysis including the non-normal distribution fit indicates an even better process capability: Cp = 2.884 and Cpk = 2.630, where the risk of producing a product outside the tolerance limits is practically negligible.
Table 3 shows a comparison of process capability indices for Hole B calculated using the normal distribution, non-normal distribution (Johnson fit) and Pearson curves.

Table 3. Normal vs Non-Normal Capability Indices for Hole B

Capability Index	Normal Distrib.	Non-Normal Distrib.	Pearsons Curves
Lower Specification Limit	6.000000		
Nominal Specification	6.020000		
Upper Specification Limit	6.060000		
Lower Perc. Value: .135	6.014883	6.020515	6.020843
Median (50%) Value: 50.000	6.030113	6.029860	6.029875
Upper Perc. Value: 99.865	6.045343	6.041320	6.041161
CP (potential capability)	1.969792	**2.883957**	**2.953062**
CR (capability ratio)	0.507668	**0.346746**	**0.338632**
CPK (demonstrated excellence)	1.962379	**2.630111**	**2.669263**
CPL (CP, lower)	1.977206	**3.195227**	**3.307691**
CPU (CP, upper)	1.962379	**2.630111**	**2.669263**
K (non-centering correction)	0.003763	**0.004653**	**0.004180**

Source: own study with the use of TIBCO Statistica 14.0

Assuming normality, the values of Cp = 1.97 and Cpk = 1.96 indicate a capable and well-centered process that meets quality requirements. However, using non-normal distributions yielded even higher values: Cp = 2.88-2.95 and Cpk = 2.63-2.67. This difference indicates that classical indices based on normality underestimate the true potential of process B. High values of CPL (3.20-3.31) and CPU (2.63-2.67) indicate a very low risk of exceeding the tolerance limits on both the lower and upper sides. A value for the K (non-centering correction) index was also calculated, which measures how far the process mean is from the center of the tolerance zone relative to half the tolerance (TIBCO Statistica 14 Electronic Manual). K values close to zero indicate that the drilling process for hole B is perfectly centered relative to the center of the tolerance zone; the process mean practically coincides with the center of the tolerance zone. Due to the fact that the limits are asymmetric, it should also be stated that the process B is centered relative to the tolerance center, but not perfectly relative to the nominal value (NOM).
The Figure 9 shows the process capability analysis of drilling Hole C, in which the non-normal distribution fitting method of moments was used.
The capability indices of process C calculated under the assumption of normality indicate values Cp = 1.861 and Cpk = 1.794, which confirms that the process meets the quality requirements, however, its capability assessed classically is lower than in the case of hole B. Taking into account the actual shape of the distribution allowed obtaining significantly higher values of the capability indices: Cp = 2.798 and Cpk = 2.743. This indicates a high level of capability of process C, and the risk of values occurring outside the tolerance limits can be considered negligible.

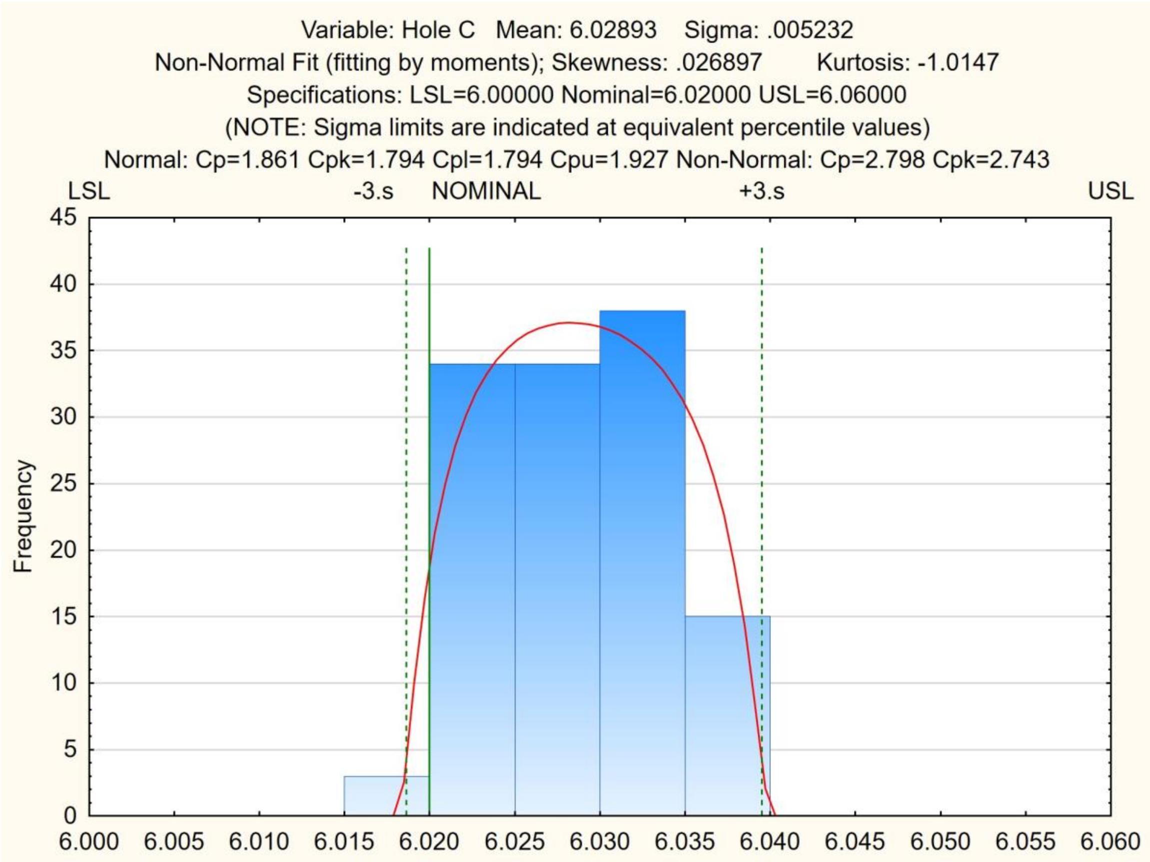

Fig. 9. Non-Normal Capability analysis for Hole C
Source: own study with the use of TIBCO Statistica 14.0

Table 4 shows a comparison of process capability indices for hole C calculated using the normal distribution, non-normal distribution (Johnson fit) and Pearson curves.

Table 4. Non-Normal Capability Indices for Hole C

Capability Index	Normal Distrib.	Non-Normal Distrib.	Pearsons Curves
Lower Specification Limit	6.000000		
Nominal Specification	6.020000		
Upper Specification Limit	6.060000		
Lower Perc. Value: .135	6.012804	6.018352	6.018636
Median (50%) Value: 50.000	6.028927	6.028878	6.028882
Upper Perc. Value: 99.865	6.045051	6.039794	6.039541
CP (potential capability)	1.860679	**2.798172**	**2.870202**
CR (capability ratio)	0.537438	**0.357376**	**0.348408**
CPK (demonstrated excellence)	1.794154	**2.743397**	**2.818946**
CPL (CP, lower)	1.794154	**2.743397**	**2.818946**
CPU (CP, upper)	1.927203	**2.850994**	**2.919472**
K (non-centering correction)	0.035753	**0.037386**	**0.037275**

Source: own study with the use of TIBCO Statistica 14.0

Assuming a normal distribution, the capabilities values are: Cp = 1.86 and Cpk = 1.79, which indicates that the process can be considered capable, but with a lower potential compared to the analyzed hole B. However, taking into account the fit to non-normal distributions allowed obtaining higher values: Cp = 2.80-2.87 and Cpk = 2.74-2.82, indicating a very high process capability and minimal risk of out-of-tolerance production. The K index values (0.035-0.037) remain close to zero, indicating that the process is well centered with respect to the center of the tolerance zone, but not with respect to the nominal value.
Table 5 summarizes the capability indices of the B and C drilling processes, calculated based on the non-normal fitting using Johnson curves and the percentile method.

Table 5. Non-Normal Capability Indices for Hole B and C

Capability Index Within-sample sigma=R-bar/d2	Non-normal (Johnson curves) (fitting by moments) capability indices (Indices computed via percentile method)														
	Const. C (±C)	Const. C (±C)	LSL	Nom	USL	Lower % Value	Median	Upper % Value	CP	CR	CPK	CPL	CPU	K
Hole B	-3.00	3.00	6.00	6.02	6.06	6.021	6.030	6.041	**2.88**	**0.35**	**2.63**	**3.20**	**2.63**	**0.004**
Hole C	-3.00	3.00	6.00	6.02	6.06	6.018	6.029	6.040	**2.80**	**0.36**	**2.74**	**2.74**	**2.85**	**0.037**

Source: own study with the use of TIBCO Statistica 14.0

The results clearly indicate that both processes have very high levels of capability – Cp values are 2.88 for hole B and 2.80 for hole C, respectively. The Cpk values confirm that both processes are not centered relative to the tolerance center. Analysis of the CPL and CPU components reveals that process B has better capability towards the lower tolerance limit (CPL = 3.20) than towards the upper tolerance limit (CPU = 2.63), while process C's capability towards both tolerance limits is more balanced, with CPL = 2.74 and CPU = 2.85. The K factor is 0.004 for hole B and 0.037 for hole C. This means that the drilling process for hole B is almost perfectly centered relative to the tolerance center, while for hole C, a slightly larger mean shift from the tolerance center towards the lower tolerance limit (LSL) is observed.
In addition to Cp and Cpk, which evaluate process dispersion relative to tolerance limits, Cpm-type indices were also calculated. These indices penalize deviations of the process mean from the nominal target, thus combining information about variability and centering accuracy (Chang et al., 1988). To address the non-normal distribution of data, the Clements percentile method was applied, replacing the standard deviation with a percentile-based equivalent of six sigma.
Table 6 presents the calculated capability indices Cpm, CpmL, CpmU, and Cpmk for drilling processes B and C. The values are shown together with the process mean (μ) and the equivalent standard deviation (σeq).

Table 6. Capability indices Cpm and Cpmk for drilling processes B and C calculated using the Clements percentile method

Process	Mean (μ)	σ_{eq}	Cpm	CpmL	CpmU	Cpmk
Hole B	6.03011	0.00177	0.974	0.649	1.299	0.649
Hole C	6.02906	0.00145	1.089	0.726	1.452	0.726

Source: own study with the use of TIBCO Statistica 14.0

The calculated values of the Cpm indices for processes B and C confirm that both processes exhibit low variability but are not ideally centered relative to the nominal value (NOM). Process C achieved slightly higher values of Cpm and Cpmk compared to process B, indicating better alignment with the target value (NOM) and a more balanced capability towards both specification limits. In contrast, process B, although characterized by comparable dispersion, showed lower CpmL and consequently a lower Cpmk, which suggests a greater risk of deviations towards the lower specification limit (LSL). These results emphasize the complementary role of Cpm-type indices in capability analysis, as they provide additional insight into the accuracy of centering that cannot be captured solely by Cp and Cpk.

The comparison of Cp/Cpk and Cpm/Cpmk indices has showed clear differences in the assessment of processes B and C. While the percentile-based Cp and Cpk indices for both processes significantly exceeded the acceptance threshold (Cp, Cpk > 2), indicating very low variability and a negligible risk of exceeding the tolerance limits, the corresponding Cpm and Cpmk values remained close to 1. This confirmed that both processes, despite their high capability in terms of tolerance conformance, were not perfectly centered with respect to the nominal value (NOM). Process C achieved higher Cpm and Cpmk values (≈1.09 and 0.73) compared to process B (≈0.97 and 0.65), which provided evidence of its better alignment with the target value and more balanced capability within the specification limits.

In summary, both processes demonstrate above-average quality capability. Drilling process B hole is characterized by better centering and higher capability towards the lower tolerance limit, while drilling process C hole is characterized by a more balanced distribution of capability throughout the tolerance field.

3.4. Summary analysis of processes B and C. Which process is better?

The comparative analysis of drilling processes B and C, based on the evaluation of process stability and capability, confirms that both processes demonstrate a high level of statistical stability and are capable of meeting the required quality specifications. Control charts constructed with the use of Johnson transformation showed that neither process exhibited points outside the control limits or signs of special cause variation, which validates their stable character.

Nevertheless, a more detailed examination reveals that process B exhibits a slightly higher level of stability compared to process C. After the Johnson transformation, the estimated standard deviation for process B is approximately 0.00508, while for process C it is approximately 0.00537, which means that the short-term variability of process B is about 6% lower. Moreover, the X-bar chart for process C shows a larger amplitude of fluctuations in the mean values around the center line. In process B, the dispersion of the means is more concentrated, indicating better repeatability of measurements and higher consistency over time.

In terms of capability, both processes achieved very high Cp and Cpk values when assessed with non-normal fitting (Johnson curves), clearly exceeding the minimum acceptance threshold (Cp, Cpk ≥ 1.33). Process B achieved Cp = 2.88 and Cpk = 2.63, whereas process C reached Cp = 2.80 and Cpk = 2.74. This indicates that both processes are highly capable, with process B showing superior capability towards the lower

specification limit (CPL = 3.20), while process C showed more balanced capability between the lower and upper tolerance limits (CPL = 2.74; CPU = 2.85).
The centering index K confirmed these observations: process B is almost perfectly centered within the tolerance field (K = 0.004), while process C shows a slight but practically negligible offset (K = 0.037).
When comparing the two processes based on Cpm and Cpmk indices, process C achieved higher values of Cpm and Cpmk (≈1.09 and 0.73) than Process B (≈0.97 and 0.65), indicating better centering and more balanced capability across the specification range. Process B, although highly capable in terms of Cp and Cpk, showed poorer alignment with the target value and a lower capability towards the lower specification limit. Consequently, process C may be regarded as superior from the perspective of achieving the nominal specification and ensuring long-term dimensional robustness.
In summary, both processes have proven to be statistically stable and highly capable of meeting the tolerance requirements. However, the extended analysis has shown that their capability differs depending on the applied indices. Process B exhibited lower short-term variability and higher CPL, confirming its strong protection against defects at the lower specification boundary. Nevertheless, its lower Cpm and Cpmk values indicated imperfect centering relative to the nominal dimension. In contrast, process C, although characterized by slightly higher variability, achieved better alignment with the target value and more balanced performance within the specification limits, as reflected in its higher Cpm and Cpmk indices. Therefore, process C can be regarded as the more advantageous option when accuracy with respect to the nominal specification and long-term capability are prioritized.
Table 7 provides a comparative summary of drilling processes B and C, based on the assessment of process stability and capability.

Table 7. Comparative Analysis of Drilling Processes B and C

Criterion	**Process B**	**Process C**	**Conclusion**
Statistical stability	Very high; no points beyond control limits; slightly higher stability than C	Very high; no points beyond control limits; slightly lower stability than B	Both stable, but B more consistent
Estimated σ (after Johnson transformation)	≈ 0.00508	≈ 0.00537	B has ~6% lower short-term variability
X-bar chart behavior	Smaller amplitude, means more concentrated	Larger amplitude, greater dispersion	B shows better repeatability
Process capability (Cp, Cpk)	Cp = 2.88, Cpk = 2.63; strong capability, especially toward LSL (CPL = 3.20)	Cp = 2.80, Cpk = 2.74; balanced capability (CPL = 2.74, CPU = 2.85)	Both highly capable; B stronger at LSL, C more balanced
Centering index (K)	K = 0.004 → almost perfectly centered	K = 0.037 → slight offset (negligible)	Both well centered; B closer to center
Capability with respect to target (Cpm, Cpmk)	Cpm ≈ 0.97, Cpmk ≈ 0.65 → poorer centering vs. target	Cpm ≈ 1.09, Cpmk ≈ 0.73 → better centering and balance	C superior in terms of accuracy and long-term robustness

Overall assessment	Lower variability, stronger protection at LSL, high Cp/Cpk, but poorer alignment with target	Slightly higher variability, but better centering and balanced capability across limits	Process C more advantageous when accuracy relative to nominal and long-term capability are prioritized

To answer the question posed for the aim of the research, which drilling process B or C is better in terms of stability, quality capability in relation to tolerance and quality capability in relation to tolerance and purpose, and why, a comparison Table 8 was developed.

Table 8. Process B and C: Which process is better and why?

Criterion	Better Process	Justification
1. Stability over time	Process B	Lower short-term variability (~6% lower σ) and smaller fluctuations around the mean indicate higher repeatability.
2. Quality capability (Cp, Cpk) relative to tolerance limits	Process C	It has a higher Cpk and is more centered (as the difference between Cp and Cpk; Cp-Cpk)
3. Quality capability (Cpm, Cpmk) relative to tolerance and target/ target-oriented capability indices	Process C	Process C is better because it has higher Cpm and Cpmk, which means it is closer to the target value and has a lower risk of producing out of specification

The analysis shows that Process B demonstrates superior stability over time, while Process C outperforms in terms of quality capability, both relative to tolerance limits (Cp, Cpk) and to the target value (Cpm, Cpmk). Therefore, when considering capability and alignment with the target, Process C should be regarded as the better process overall.
Reducing short-term and long-term variability in the drilling process requires implementing a number of key organizational and technical measures. First, it is necessary to ensure the consistency of drilling parameters by eliminating accidental modifications by operators. The next step is systematically replacing tools according to established wear limits, which helps prevent sudden deviations in hole quality. Ensuring repeatable workpiece clamping is also crucial. Furthermore, the drilling process must be supported by the proper functioning of the cooling system. During production, ongoing measurements for SPC analysis are essential, as limiting the inspection to final inspection delays problem detection and increases the risk of scrap. In the long term, scheduled machine inspections are essential. A consistent policy of purchasing tools from trusted suppliers is also crucial. Process repeatability can also be enhanced through operator training and the use of uniform work instructions that minimize variations between shifts. Finally, the use of statistical process control and trend analysis on SPC charts allows for the identification of special signals and the implementation of corrective actions before serious discrepancies occur.

4. CONCLUSION

The aim of the study was to evaluate the stability and capability of the drilling processes using statistical process control (SPC) tools to identify the superior process in terms of both process evaluation criteria.

The study confirmed that the two drilling processes analyzed (holes B and C) were statistically stable and highly capable of meeting the specified dimensional requirements. Johnson transformed $\bar{X}$ control charts showed no signs of drift or special causes, confirming the stability of both processes over time.

Analysis of capability indices calculated using the Clements percentile method confirmed that both drilling processes significantly exceeded the minimum acceptance thresholds (Cp, Cpk ≥ 1.33), indicating a negligible risk of producing out-of-tolerance parts. Nevertheless, notable differences were identified: process B exhibited lower short-term variability, nearly perfect centering within the tolerance field, and superior performance with respect to the lower specification limit (LSL). In contrast, Process C, although characterized by slightly greater variability, demonstrated better alignment with the nominal specification and a more balanced capability across the entire tolerance range, as reflected in its higher Cpm and Cpmk values.

These results highlight the importance of combining stability, capability, and accuracy-to-target assessments to obtain a complete picture of process performance, particularly when dealing with asymmetric specification limits. The application of methods adapted to non-normal data, such as Johnson transformations and percentile-based capability indices, provided a reliable evaluation of the actual process behavior. From a practical standpoint, both processes are robust and suitable for continued serial production without the need for corrective actions, while process C provides a clear advantage by maintaining closer alignment with the nominal dimension and offering more balanced capability across the entire tolerance range. Overall, while process B shows superior stability, process C should be regarded as the better process due to its higher capability indices (Cp, Cpk, Cpm, Cpmk) and closer alignment with the nominal specification.

The analysis was conducted on a single product and two machining operations performed under specific batch production conditions. Therefore, the results cannot be directly generalized to other products, materials, or machining configurations.

Further research will focus on defining comparative criteria for assessing the quality of multi-stream processes (MSP), generating several product streams (e.g., a filling process used in the food industry, where a filling machine may have multiple filling heads), using Statistical Process Control (SPC) tools, in order to develop a ranking system for such processes based on the stability and capability analysis.

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