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Statistical Analysis of Process Capabilities in 3D Printing for Evaluating Vertical and Horizontal Object Precision

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Abstract

As 3D printing technology advances, the demand for precise, reliable production methods grows, with tighter product specifications and higher quality standards becoming essential. This study focuses on students learning experience as they explore the statistical analysis of process capabilities in 3D Printing, specifically assessing the accuracy and precision of vertically and horizontally printed objects. Through hands-on experimentation, students gain valuable skills in evaluating critical factors influencing 3D printer performance, such as geometry, material selection, and printer settings. The research enables students to assess the process limits of 3D printers and develop strategies to minimize variability and improve production quality. Students learn how these factors affect the final product by experimenting with different printer configurations, internal designs, and operational parameters. The study also highlights cost-effective solutions by identifying print settings that optimize performance and reduce defects. Ultimately, this learning experience deepens students understanding of 3D printing process control, enhances their ability to make data-driven decisions, and equips them with practical knowledge for improving efficiency in advanced

manufacturing applications.

Keywords
Statistical analysis, 3D Printing, process capabilities, precision.

1. Introduction
Recently, 3D Printing has become a transformative force in manufacturing, significantly advancing industries such as mechanical, electrical, biomedical, and aerospace by improving design processes, minimizing lead times, and reducing tooling costs for new component production (Zaneldin, E et al 2021) Unlike traditional machining methods like turning, milling, and drilling, which were widely used in the past but are now less favored due to high production costs, 3D Printing, also known as additive manufacturing, builds products layer by layer from digital designs (Ahmed, W, 2020). The quality of 3D-printed products depends on factors such as material composition, manufacturing process, printer speed, printer type, and the volume of the printed part. This technology has profoundly impacted many fields (Aldarmaki, A. N. et al.,2019) including prototyping, simulations, and failure analysis (A. H. Al-Shamsi et al, 2019) The aerospace industry, in particular, has benefited from 3D Printing in a broad range of applications (K. A. Awad Alahbabi et al 2019). Additionally, 3D Printing is increasingly being adopted in educational settings, from schools (W. K. Ahmed and I. M. Alhamad, 2018) to universities (Alhamad, Issah, et al,2019)where it is used to enhance learning and hands-on experience. A research study examined the impact of process parameters, such as layer thickness and raster angle, on the linear and radial dimensional accuracy of Poly polypolylactic components produced using Fused Deposition Modeling (W. K. Ahmed and H. Z. Ali, 2019). The findings revealed that the dimensions of the fabricated parts were smaller than the original CAD model, attributed to material shrinkage during the cooling phase following layer deposition. The radial dimension (RD) exhibited more significant dimensional inaccuracy than the linear dimension, due to the slicing process and the squaring of edges. The International Tolerance Grade (IT-grade) was applied to LD and RD to evaluate the dimensional precision. IT grade, a standard measure for dimensional accuracy in machining, indicated that the linear dimension had a lower IT-grade, signifying better accuracy than the radial dimension. Furthermore, the IT-grade remained consistent within a specified range throughout the experiments (Maurya, N. K., 2019).

In another study, the mechanical performance of 3D-printed parts with a Honeycomb internal pattern fabricated via Fused Deposition Modeling (FDM), was analyzed using statistical methods. The Honeycomb pattern was selected for its superior ability to withstand mechanical loads. Critical process parameters, including layer thickness, infill percentage, and extruder temperature, were controlled using 3D slicing software, and the parts were evaluated based on build time, maximum failure load, elongation at break, and part weight. Response Surface Methodology was used for analysis. The results showed that layer thickness was the most significant factor affecting all output responses. Additionally, the interaction between infill percentage and extruder temperature notably impacted elongation at break, influencing fracture severity and build time reduction (Moradi et al ,2019). In recent years, there has been less focus on the dimensional accuracy of internal structures compared to the mechanical properties of 3D-printed parts. To address this gap, a study assessed and compared the dimensional accuracy of internal structures using various scanning strategies. The results indicated that internal structures printed along the scanning direction were more dimensionally accurate than those printed vertically relative to the scanning direction. Finite Element Analysis (FEA) demonstrated that temperature distribution along the scanning path was more uniform in the horizontal direction. At the same time, vertical Printing resulted in more significant dimensional deviation due to uneven temperature distribution (Han, J et al, 2019).

2. Experimental Procedure
This experiment aimed to engage students with the practical side of statistics so they are familiar with their real engineering life (Batson, R, 2019) through evaluating the process capability of 3D-printed PLA discs using different infill patterns and orientations to understand how these factors influence dimensional accuracy. The experiment was conducted using an Ultimaker UM S5 3D printer equipped with a Core Print AA 0.4 nozzle, set to normal printing mode to simulate standard production conditions. Besides, Cura slicer has been used to convert geometries to G-code for printing purposes. The target dimension for each disc was a diameter of 22 mm, a thickness of 4mm, and the infill density was fixed at 20%, a standard setting that balances strength and material efficiency. The geometry and orientation of the models considered are shown in Figure 1.

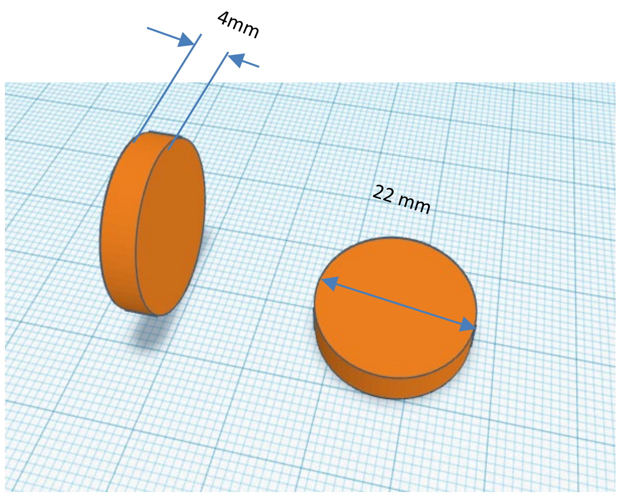

Figure 1. Dimension of the 3D Printed PLA discs

For this study, six infill patterns were selected: Grid, Line, Triangle, Concentric, Cross, and Gyroid. The discs were printed in two different orientations to assess the effect of print direction on process capability: vertically and horizontally. This allowed for a comprehensive comparison of how orientation and infill patterns influence print quality and accuracy. Figure 2 illustrates the slicing process of the study geometries and the triangular infill pattern as a sample at 20% infill density.

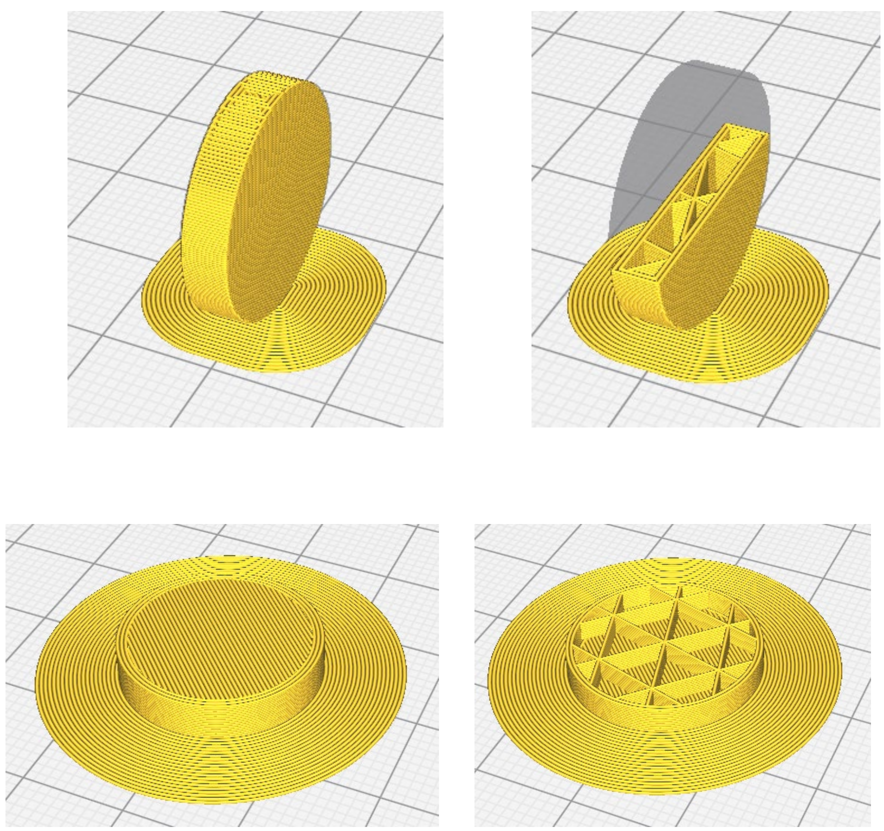

Figure 2. Triangular infill pattern as a sample at 20% infill density

After Printing, the dimensional accuracy of each disc was assessed by measuring the diameter in multiple locations. A Mitutoyo digital caliper with a precision of 0.01 mm, featuring a convenient button for quick measurements, was used for dimensional accuracy assessments. The caliper was used to measure four different points on each disc to ensure thorough data collection. Measurements were recorded in three orientations: horizontally, vertically, and along diagonal lines, providing a broad understanding of any variability or deformation caused by the infill pattern or print orientation. The target diameter for each disc was 22 mm, with acceptable variation defined by an Upper Specification Limit (USL) of 22.03 mm and a Lower Specification Limit (LSL) of 21.97 mm. The measurements for each disc were collected and tabulated for further statistical analysis. By capturing data for each infill pattern and orientation, students could calculate process variability and understand how different print settings impact the final product quality. This hands-on approach using a professional-grade 3D printer, like the Ultimaker UM S5, gave students valuable insights into manufacturing processes. It allowed them to explore the real-world implications of print design and machine settings on dimensional accuracy while applying statistical tools such as process capability indices to evaluate the effectiveness and consistency of the printing process.

3. Hypothesis of the Study Toward Learning Experience:

3.1 Null Hypothesis:

Engaging in hands-on 3D printing and process capability analysis does not significantly enhance students understanding of statistical concepts, such as Cp and Cpk, or their ability to apply these concepts in real-world manufacturing scenarios. The learning experience gained through this practical approach is not substantially different from traditional classroom-based learning (Montgomery, D. and Runger, G. 1995).

3.2 Alternative Hypothesis

Engaging in hands-on 3D printing and process capability analysis significantly enhances students understanding of statistical concepts, such as Cp and Cpk. It improves their ability to apply these concepts in real-world manufacturing scenarios. This practical learning experience provides more profound perceptions and a sufficient understanding of statistical methods than traditional classroom-based learning.

This hypothesis will be evaluated by assessing students comprehension, engagement, and application of statistical tools in a 3D printing context, comparing their performance before and after the hands-on experience.

4. Vertical Printing Case Study

The process capability analysis for the six infill patterns Grid, Line, Triangle, Concentric, Cross, and Gyroid, when printing discs vertically reveals distinct differences in performance, as shown in Figure 3 and Figure 4. The Gyroid pattern exhibits the best overall process capability, with a Cp of 2.82 and a Cpk of 1.434, indicating that it is both highly capable and well-centered within the specification limits. This makes Gyroid the most reliable option, approaching Six Sigma quality, although it falls just short of the strict requirement of a Cpk of 2 for Six Sigma. The Triangle pattern also demonstrates strong capability, with a Cp of 1.88, but its Cpk of 0.815 suggests it is slightly off-center, though still relatively close to the desired range. In contrast, the Grid, Line, Concentric, and Cross patterns fall short of acceptable process capability, with Cp values all below 1. Grid and Cross are particularly poor performers, with negative Cpk values (-0.015 and -0.229, respectively), indicating that their processes are incapable and misaligned with the specification targets. While Line and Concentric perform better in variability (Cp values of 0.638 and 0.423), their centering remains problematic, as reflected in their low Cpk values. Overall, only the Gyroid and Triangle patterns are deemed acceptable for maintaining consistent quality, with Gyroid emerging as the most reliable for this specific application.

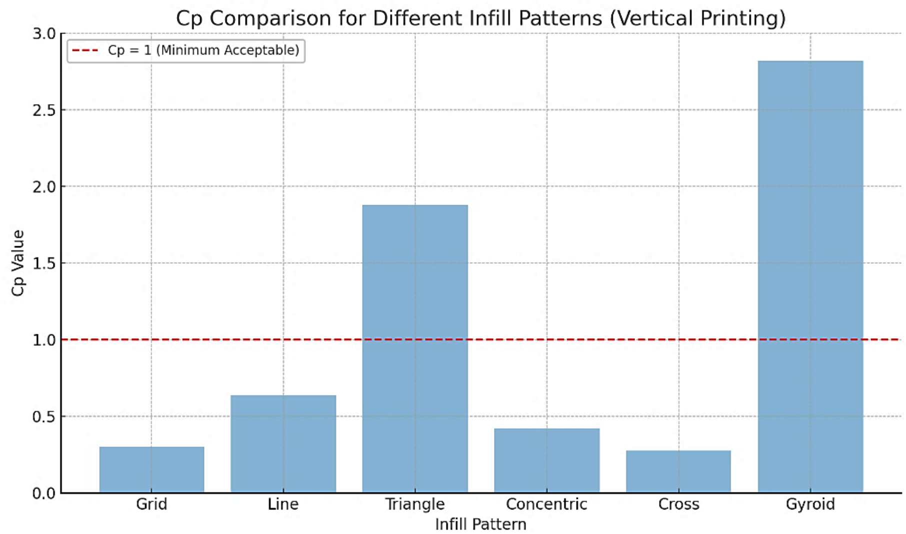

Figure 3. Cp Comparison for Vertical Printing Infill Patterns.

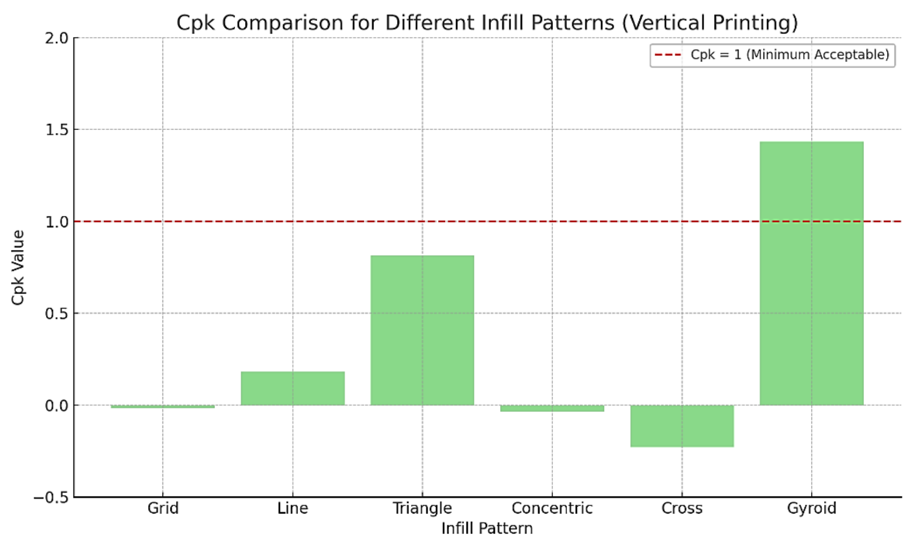

Figure 4. Cpk Comparison for Vertical Printing Infill Patterns.

5. Horizontal Printing Case Study

The process capability analysis for the six infill patterns Grid, Line, Triangle, Concentric, Cross, and Gyroid, when printing discs horizontally reveals significant differences in performance as illustrated in Figure 5 and Figure 6. The Cross and Concentric patterns stand out with exceptionally high Cp and Cpk values, making them the top-performing options. Cross has a Cp of 8.46 and a Cpk of 5.922, while Concentric shows a Cp of 5.64 and a Cpk of 3.901. These values far exceed the Six Sigma threshold (Cpk ≥ 2), indicating outstanding process control and centering, and they meet Six Sigma standards with corresponding Sigma levels of 17.77 and 11.70, respectively. The Grid pattern also demonstrates strong process capability with a Cp of 2.417 and a Cpk of 1.188, although it is not perfectly centered within specification limits, with a Sigma level of 3.564. On the other hand, Line and Triangle have acceptable Cp values of 1.167 and 1.991, respectively, but their Cpk values (0.71 and 0.697) indicate they are not centered well, leading to potential defects. Finally, the Gyroid pattern is on the borderline of acceptability, with a Cp of 0.995 and a Cpk of 0.796, showing that it struggles to maintain capability and centering. In summary, Cross and Concentric are the most reliable infill patterns for horizontal Printing, while Grid is capable but could benefit from better centering. Line, Triangle, and Gyroid require improvements in centering to enhance their overall performance.

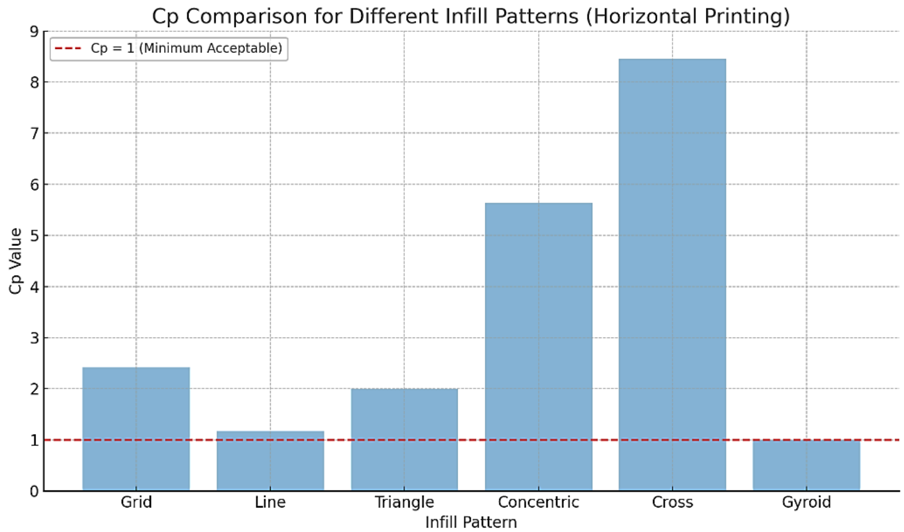

Figure 5. Cp Comparison for Horizontal Printing Infill Patterns.

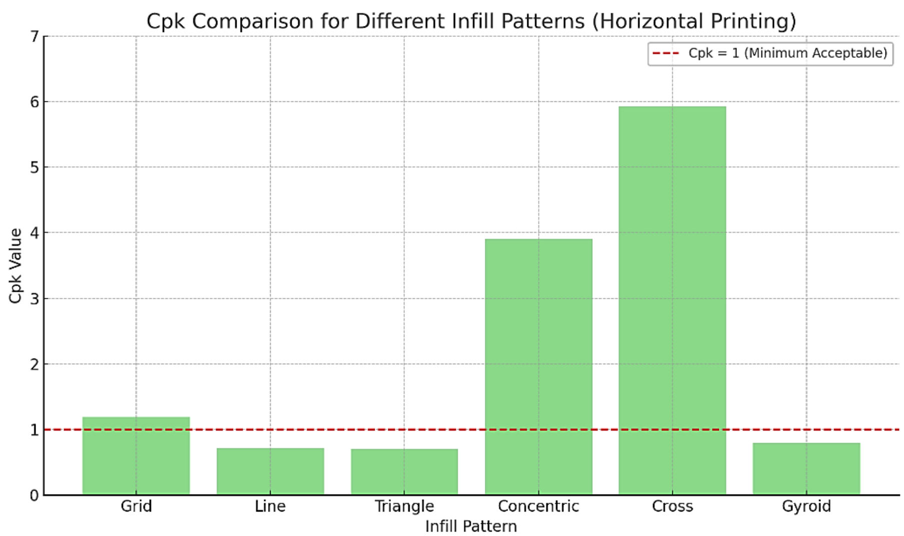

Figure 6. Cpk Comparison for Horizontal Printing Infill Patterns

6. Comparison Analysis

The visualization compares the Cp values for each infill pattern between vertical and horizontal Printing, as depicted in Figure 7. It is evident that horizontal Printing consistently results in much higher Cp values for all patterns than vertical Printing. In a summary, students could conclude that:

- Cross and Concentric show extremely high Cp values in horizontal Printing, indicating excellent process capability, while in vertical Printing, their Cp values are significantly lower and fall below the acceptable threshold of 1.
- Gyroid and Triangle patterns also perform better in horizontal orientation, with Cp values well above 1, whereas in vertical Printing, Gyroid barely exceeds 1, and Triangle is the only acceptable pattern.
- Line and Grid have moderate Cp values in horizontal Printing, with Grid exceeding 2 and Line slightly above 1. In vertical Printing, both patterns struggle, falling short of acceptable capability levels.

Accordingly, students could understand and conclude that horizontal printing orientation is generally more favorable for maintaining process capability, resulting in less variability and higher dimensional accuracy for all infill patterns

(ENGLISH, L. , 2023).

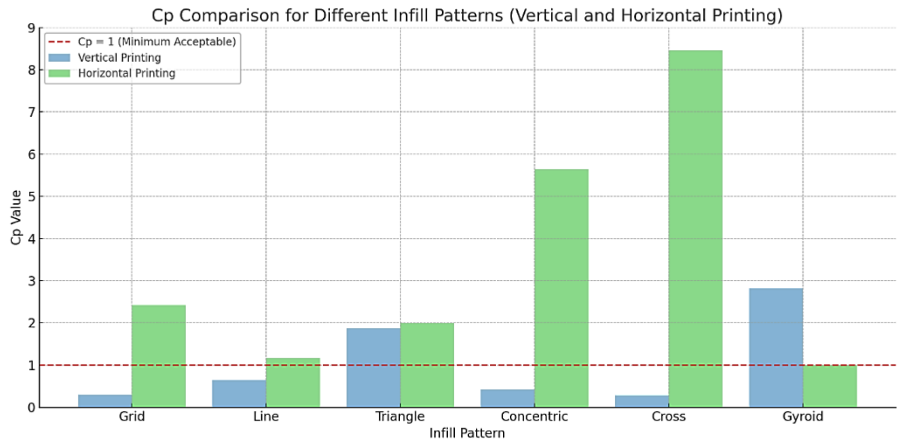

Figure 7. combined CP Comparison for Vertical and Horizontal Printing Infill Patterns

On the other hand, the comparison of Cpk values between horizontal and vertical printing orientations shows a significant improvement in the horizontal orientation across all infill patterns, as shown in Figure 8. Students could summarize the observations as follows:

- Cross and Concentric exhibit the highest Cpk values in horizontal Printing, far exceeding the acceptable threshold of 1. In contrast, their vertical values are negative, indicating poor centering and high variability when printed vertically.
- Gyroid performs much better in vertical Printing with a Cpk of 1.434 compared to its horizontal value of 0.796, though it is still below the Six Sigma threshold in both orientations.
- Grid performs acceptably in horizontal Printing (Cpk = 1.188) but struggles in vertical orientation (Cpk = -0.015).
- Line and Triangle patterns show improved but still suboptimal performance in horizontal Printing, with Cpk values below 1, while their vertical Cpk values are even lower.

Students generally recognized that horizontal Printing produces much better centering and consistency across most patterns, making it a more reliable orientation for achieving higher process control and quality (Silvaet al. 2020).

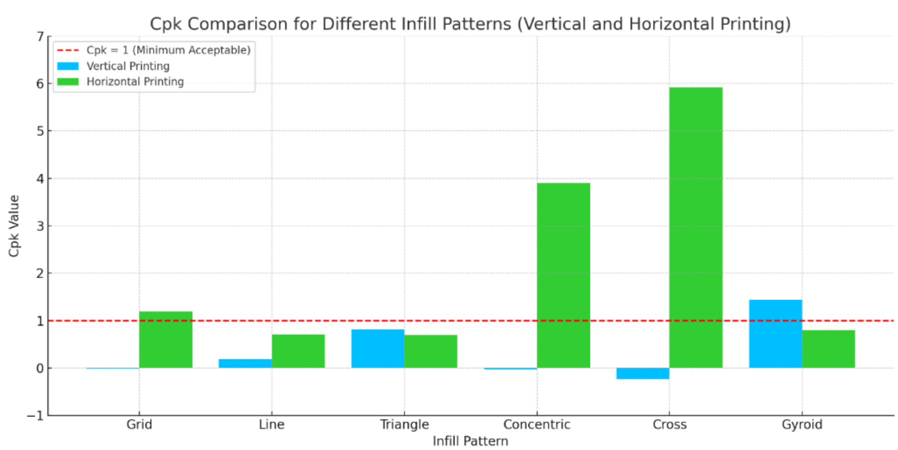

Figure 8. Combined Cpk Comparison for Vertical and Horizontal Printing Infill Patterns

7. Conclusions

The experiments on process capability using different infill patterns and orientations in 3D Printing provide a valuable learning experience for students studying statistics, quality control, and manufacturing processes. By measuring the dimensional accuracy of 3D-printed PLA discs and analyzing the data through Cp (process capability index) and Cpk (centering index), students gain hands-on exposure to the real-world application of statistical tools in manufacturing. The comparison of vertical and horizontal printing orientations highlights the importance of understanding and managing process variability. Students can see how data driven decisions, such as choosing the right print orientation, can significantly improve product quality. Patterns such as Cross and Concentric performed best in horizontal Printing, demonstrating how different design choices affect process outcomes, while vertical Printing showed challenges in maintaining consistent quality. This contrast provides a rich opportunity for students to interpret and analyze statistical results, identifying areas for improvement and optimization. Through this exercise, students apply statistical concepts like standard deviation, process capability, and Six Sigma and learn the importance of data collection, measurement precision, and critical thinking in addressing real-world manufacturing issues. This combination of theory and practice helps solidify their understanding of statistics and its role in ensuring quality in industrial applications. The hands-on exploration of 3D printing and process capability analysis offers students a rich learning experience that bridges theoretical concepts with real-world applications. Students understand how these factors influence printed objects accuracy, precision, and overall quality through experimenting with different infill patterns, orientations, and printer settings. Through data collection and statistical tools like Cp and Cpk, students develop practical skills in assessing and optimizing the performance of 3D printers. This approach enhances their ability to make data-driven decisions and fosters critical thinking in problem-solving for manufacturing processes.

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