International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 16s,2025
https://theaspd.com/index.php

Enhancing Quality And Reducing Defects Through Statistical Process Control At Abc Manufacturing Limited

DEEPAK RAVINDRA PATIL[1], **DR. KASI RAJA RAO**[2], **DR. S. T. PURKAR**[3]
[1]PhD Scholar, Mandsaur University M.P., India
[2]Assistant Professor, Mandsaur University M.P., India
[3]Director, SKITM College Indore (M.P.), India
[1]deepak.patil338@gmail.com, [2]krajarao218@gmail.com, [3]sanjaypurkar@skitm.in

Abstract

Acquiring superior product quality together with reducing manufacturing defects stands as an essential requirement to boost operational performance and enhance customer satisfaction in modern manufacturing operations. Both higher rework expenses and scrapped products along with lowered brand quality result in decreased market capitalization for companies. Statistical Process Control (SPC) functions as a fundamental quality management solution through its data-oriented analysis which gives producers daily control over manufacturing parameters. ABC Manufacturing Limited which produces Y9T Calipers seeks to implement SPC for their key component production of Main Bore, Seal Groove and Lug Hole to achieve better product quality and defect reduction. This research uses process variable adjustments of spindle speed and cutting depth alongside feed rate to enhance process capability indices Cp and Cpk which leads to lowered manufacturing prices. Through the implementation of control charts together with Pareto analysis and regression models the specific parameters were tracked and optimized for better product consistency alongside cost-effective results. The outcome demonstrates that purposeful SPC interventions create high-quality results while decreasing defects and increasing process speed so manufacturing operations gain large financial advantages.

Keywords: *ABC Manufacturing Limited, Main Bore, Lug Hole, Seal Groove, Statistical Process Control, Y9T Calipers*

1. INTRODUCTION

Manufacturing organizations need to focus permanently on product quality and defect reduction to succeed in the competitive industrial environment. Manufacturing defects represent a major obstacle to operational efficiency because defective products require additional costs to fix them and these expenses include rework efforts along with wasted materials and warranty obligations along with diminished customer satisfaction. Manufacturing defect reduction forms an essential objective that companies use to boost their operational effectiveness. ABC Manufacturing Limited operates as a leading Y9T Caliper manufacturer while dealing with the problem of product defects which affect quality and drives up production expenses. The organization needs procedures to make its process performance better and decrease manufacturing defects during operations. SPC techniques represent one of the most effective solutions to handle these problems because they use data-based approaches for processing and optimizing production methods. Statistical Process Control (SPC) functions as an established methodology because it utilizes statistical tools and techniques for real-time manufacturing process supervision and enhancement and maintenance activities. SPC serves the main objective to detect process variation sources while tracking their current changes through real-time monitoring to prevent quality defects from appearing. Manufacturers who analyze production data as it accumulates will sustain process performance control thus guarantee product specifications remain consistent throughout production. Through SPC manufacturers achieve superior quality outcomes because the system allows them to detect problems quickly followed by timely resolutions that prevent problems from worsening. ABC Manufacturing Limited needs to implement SPC for Y9T Calipers because high-quality manufacturing standards represent a critical requirement for this essential product. The Y9T Caliper serves as a vital automotive system component so any functional or dimensional defects create major impacts to safety together with performance features. Minor manufacturing deviations tend to compound into expensive defective products that degrade product quality along with damaging the company's brand reputation and customer happiness. SPC sets forth an organized system to enhance component quality production while reducing process variability and maintaining operational control parameters in the manufacturing process.

The research investigates SPC applications toward improving quality and decreasing defects during Main Bore, Seal Groove and Lug Hole production steps of Y9T Calipers made at ABC Manufacturing Limited. The Y9T Caliper depends on these essential manufacturing operations to ensure its quality for safe performance since any component defects can cause product failure. Speed variations of the spindle in combination with feed rate variations and changes in cutting depth apparently cause final product defects. SPC techniques will help this research to discover sources of variation in these operations so it can establish corrective solutions for better product quality alongside lower defect occurrence.

SPC employs control charts to track process stability across different parts of time. X-bar and R-charts function to determine if production remains stable or contains any deviations that can generate product defects. The process capability indices (Cp and Cpk) evaluate the performance of the process in comparison to its specification constraints. Cp evaluates the process capability to generate products within their specification region but Cpk indicates the process centering accuracy regarding its target specification. The precise level of process enhancement for defect decrease gets established through these significant indices. Pareto analysis enables this research to identify major defect causes by integrating it with control charts and process capability analysis. According to the Pareto principle only a few important factors lead to most production defects. To find effective solutions for defect origins the company needs to direct its capabilities toward these essential factors. The distribution of defects and process variation becomes more evident through histograms and scatter plots while revealing the effects of production parameters on final product quality. This research evaluates the effect that modifying spindle speed together with feed rate and cutting depth parameters has on defect frequency in the Main Bore, Seal Groove and Lug Hole production operations. The technical parameters directly affect the accuracy of dimensions together with the surface quality of fabricated parts. The material treatment depends on spindle speed and feed rate controls the tool movement and the cutting depth establishes the material elimination rate. Changes in process parameters produce several quality defects including mechanical and surface problems and dimensional alignment errors. The use of SPC techniques to optimize these parameters leads to diminished product defects and quality upgrades of the end product. The examination explores the monetary effects which emerge when SPC implementation happens in manufacturing operations. Both defects and poor quality costs in manufacturing result in substantial financial burdens for operations. Quality-related expenses include rework costs along with scrap expenses and inspection fees and warranty cost as part of total quality costs. Production expenses decrease substantially when SPC decreases the number of product defects. The study evaluates how SPC implementation leads to monetary savings by quantifying its effects on defect reduction. A cost-benefit analysis of SPC allows the assessment of how this system impacts operational efficiency and profitability across the long term. This research looks into quality improvement sustainability practices as a part of its assessment. Companies now require increased quality in their products while customers demand better quality standards thus making consistent quality maintenance across time more vital. The results of this study will enable ABC Manufacturing Limited to strengthen its continuous improvement initiatives which apply SPC principles for measuring and exceeding customer standards.

Key Contributions of the Study: The research adds to manufacturing knowledge applied to Statistical Process Control (SPC) through examination of these main aspects:

- Defect reduction through SPC tools: The research demonstrates how process variability gets monitored and controlled using tools like control charts together with Pareto analysis and process capability indices which decreases defects.
- Optimization of process parameters: The study shows that quality enhancement can be achieved by modifying spindle speed and feed rate together with cutting depth adjustments even though these changes remain minor.
- Financial impact: This research examines how process improvement and defect reduction can save manufacturing costs and validates the financial advantages that come from SPC implementation in industrial operations.
- Long-term sustainability: SPC enables manufacturers to achieve ongoing quality control alongside efficiency maintenance and sustained quality standard fulfillment according to the study.

2. LITERATURE REVIEW

The most powerful strategy for quality maintenance in manufacturing is Statistical Process Control (SPC). The system enables manufacturers to watch production operations in real-time so they can maintain product requirements with few mistakes. The authors of [1] demonstrate that SPC serves an essential function in manufacturing since it enables early warning of process variations which results in defect prevention before occurrence. Control charts function as one of the fundamental SPC tools that record production information to detect all deviations from predefined product specifications.

Correct application of SPC leads to improved quality as well as operational efficiency. The research publication [2] details how SPC function works as a process instability detection system which helps manufacturers prevent quality defects by intervening before they develop this leads to less product waste and fewer reworks. SPC implementation requires focus on different manufacturing industries but demands highest emphasis in aerospace and automotive fields due to their stringent quality requirements. Six Sigma serves as an advanced manufacturing quality improvement method that enhances SPC functionality to achieve superior control of manufacturing processes. Stage-by-stage process consisting of DMAIC tools allows SPC to fulfill its potential for achieving maximum defect reduction according to research in [3]. The combined approach enables manufacturers to use data for underlying defect resolution which reduces costs as well as defects significantly. The authors of paper [4] examine how Six Sigma approaches integrate with SPC through statistical processes designed to optimize production systems. The correlation of these methods functions best in sectors which run extensive production and need rigid quality assurance measures because defective items can risk safety in instances like automotive manufacturing. PCAs function as an essential SPC methodology which determines if production systems can create items that satisfy product specifications. The authors of [5] explain that PCA enables researchers to calculate Cpk and Cp indices that evaluate the consistency of processes with respect to specification limits. Product quality and defect reduction improve when process variations remain small based on high Cp and Cpk measurement results. PCA serves as an essential method for businesses to both identify unwanted process instability as well as make necessary corrections according to [6]. The regular analysis of process capability enables manufacturers to prevent product defects and decrease expenses on non-compliant items because it ensures processes stay within their defined tolerance ranges.

Every manufacturing facility puts defect reduction at the top of its objectives. SPC acts as an essential tool which identifies defects by tracking essential process parameters including spindle speed, feed rate and cutting depth according to the studies in [7] and [8]. Microsoft SQL Server supports variation identification of these parameters so preventive actions can stop defects during production. The articles in [9] explain the value of SPC tools including control charts and Pareto analysis because they help manufacturers prioritize corrective actions when searching for defects' primary origin points.

The authors of [10] present evidence about how SPC implementation enables manufacturers to optimize essential production parameters which results in superior process capability and fewer production defects. The authors show that companies that monitor their production parameters leading to parameter adjustments will reach superior product quality and better resource utilization which results in reduced operational expenses and waste. Manufacturers realize major expense reductions when they deploy SPC systems for their operations. The authors of [11] and [12] demonstrate how SPC helps manufacturers decrease their expenses by eliminating defects with waste reduction and reducing reworked materials. The authors in [13] exhibit how SPC helps decrease inspection expenses because it keeps processes within specifications which results in less additional quality testing. The authors in [14] prove how Statistical Process Control achieves improved product quality while simultaneously decreasing overall financial expenses due to scrap and rework and warranty claims. SPC generates long-term financial advantages through its ability to improve profitability by using process control to reach higher levels of product quality. Technology advances have made possible new optimizations in the fields of SPC. SPC has undergone significant transformation in its applications through its combination with Industry 4.0 technologies that include IoT devices and machine learning and big data analytics systems. The authors in [15] explain that IoT devices track manufacturing processes in real time to identify defects and ineffectiveness with SPC analysis tools. Real-time monitoring through SPC permits manufacturers to take swift action on process deviations that stops defects from developing.

The application of machine learning algorithms stimulates SPC to predict further outcomes effectively. Process failures in manufacturing can be anticipated utilizing machine learning algorithms which analyze past SPC data for manufacturers to prevent actual faults according to the research in [16]. The authors of [17] demonstrate the application of artificial intelligence (AI) in SPC for optimizing production parameters which creates dual benefits of enhanced process performance and improved product quality. SPC provides beneficial outcomes for small manufacturing operations just as much as it does for large industrial production. The authors of [18] prove SPC delivers essential advantages to small manufactories which enables them to achieve better quality outcomes with fewer complex systems at low expense. Small production facilities that decide to use fundamental SPC instrumentation can reach top standards in quality control and operational performance. The authors of [19] present evidence about small manufacturers adopting efficient SPC systems which detect process variations to enhance product quality and minimize expenses. The authors in [20] anticipate that SPC will continue developing with technological innovations which will focus on predictive analytics and immediate process optimization. SPC will become more effective after integrating emerging technologies which will help manufacturers maintain their competitiveness through higher quality and efficiency performance in a complex manufacturing environment.

3. PROPOSED METHODOLOGY

This study presents a methodology designed to improve quality together with reduced defects at ABC Manufacturing Limited through process optimization of critical parameters using Statistical Process Control (SPC) for Y9T Caliper manufacturing (Figure 1). The method used studies three essential production parameters including spindle speed feed rate and cutting depth across the production steps Main Bore Seal Groove and Lug Hole. The section details how SPC tools work through control charts and process capability analysis and regression models for reducing defects and optimizing processes.

Each step is detailed in the following sections and the theoretical foundation and mathematical formulations are included for each step.

3.1 Problem Identification and Process Selection

The proposed method requires identifying key production stages along with the elements which control product defects as its initial point. The Y9T Calipers develop most defects because of inconsistent spindle speed together with feed rate changes and different cutting depth levels. Such process variations create dimensional problems combined with surface defects while affecting product quality standards and driving up expenses. The attention on key operational parameters allows us to implement specific SPC interventions.

3.2 Data Collection

The collection of process variable measurements and their related product quality data stands essential for performing effective SPC implementation. The data should include:

- Process Parameters:
    - S stands for Spindle Speed whereas its measurement unit is RPM (Revolutions Per Minute).
    - The measurement unit for feed rate (F) is millimeters per minute (mm/min) as it expresses this variable in millimeters during one minute.
    - The evaluation system uses Cutting depth (C) as a variable which measures in millimeters.
- Product Quality Characteristics:
    - The dimensions of Main Bore together with Seal Groove and Lug Hole represent dimensional accuracy characteristics.
    - Surface finish (e.g., roughness values)

A collection of adequate parts will be obtained across different production times to obtain meaningful statistical results (50–100 units will suffice as an example).

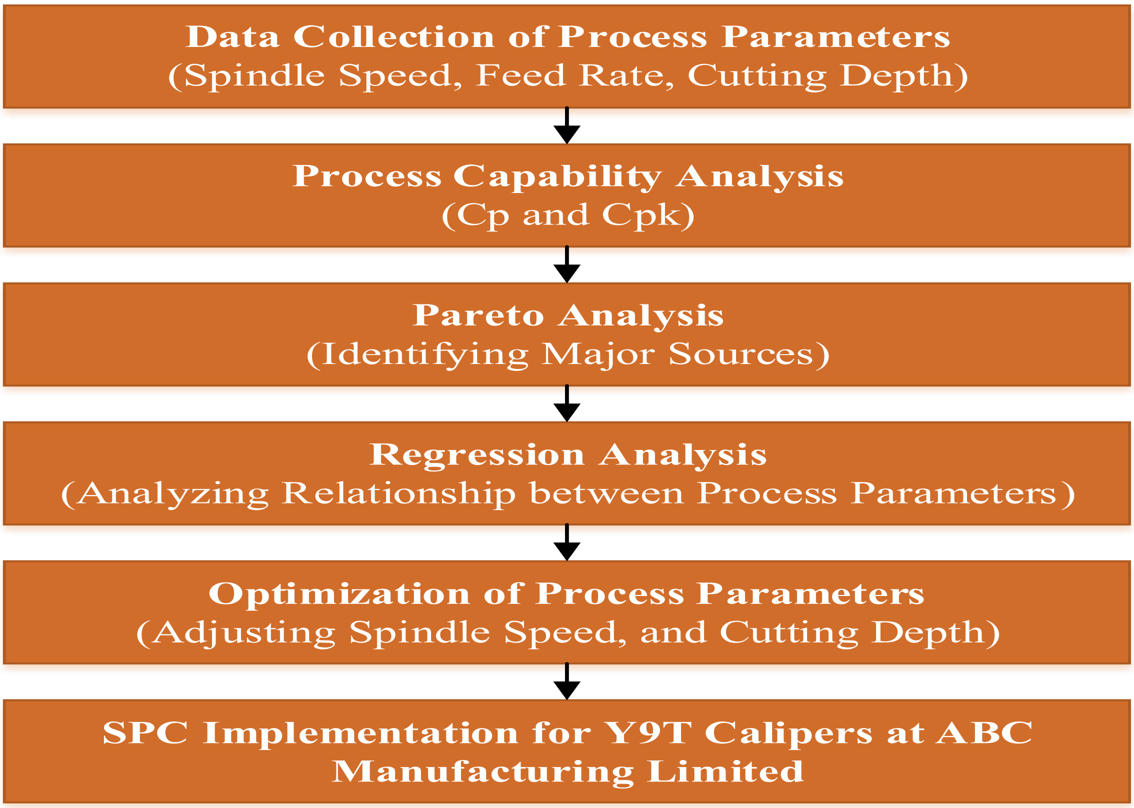

Figure 1: Flowchart of the Proposed Methodology for Enhancing Quality and Reducing Defects through SPC

3.3 Statistical Process Control Tools

3.3.1 Control Charts

Time-based monitoring functions of control charts help manufacturers determine the process stability. X-bar and R-charts will track process performance for the process parameters which include spindle speed feed rate along with cutting depth.

- The X-bar chart produces charts that display sample average measurements.

$$\overline{X}_i = \frac{1}{n}\sum_{j=1}^{n} X_{ij}$$

(1)

The analysis utilizes X_{ij} as the j^{th} measurement within the i^{th} sample as it operates on n samples.

- The R-chart reveals information about the sample measurement spread range.

$$R_i = \max(X_{ij}) - \min(X_{ij})$$

(2)

Here, R_i is the range calculation for sample i includes all measurements as X_{ij} values.

The calculation methods for control limits exist for these two charts:

$$UCL = \overline{X} + A_2R$$

(3)

$$LCL = \overline{X} - A_2R$$

(4)

Where:

- UCL and LCL symbolizes for the upper and lower control limits.
- The sample size determines A_2 of the constant value ($A_2 = 0.577$ when $n = 5$).
- The average range of the sample is known as R.

The process stability assessment becomes possible through monitoring these control charts because any parameter exceeding the control limits requires corrective actions.

3.3.2 Process Capability Analysis

The process capability evaluation depends on the Cp and Cpk indices for testing product specification achievement. Process indices provide assessment of a process capability to generate outputs within defined operational boundaries.

- **Cp (Process Capability Index):**

$$C_p = \frac{USL - LSL}{6\sigma}$$

(5)

Where:

- USL = Upper Specification Limit
- LSL = Lower Specification Limit
- σ = Standard deviation of the process

- **Cpk (Process Performance Index):**

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

(6)

Here, μ represents the mean of the process.

The process requires process improvement techniques when Cp or Cpk values fall below 1.

3.3.3 Pareto Analysis

The most important defect origins will be uncovered through execution of Pareto Analysis. The method relies on the 80-20 principle to demonstrate that a few sources generate most process issues. The steps involved are:

- The collection of defect information must span a time period.
- Organize the defects into separate categories according to their origin and classification.
- Review the frequencies of which particular defects occur.
- Rank defect types according to their recorded frequencies in descending measurements.
- A Pareto chart must be developed with defect categories placed on the x-axis and frequency displayed on the y-axis.

The organization should direct its repair work to address major defect origins that significantly affect product quality through Pareto analysis.

3.4Regression Analysis for Process Optimization

The analysis will utilize regression models to establish correlations between spindle speed along with feed rate and cutting depth as process variables and product quality characteristics such as dimensional accuracy together with surface finish. The multiple linear regression model demonstrates the following form:

$$Y = \beta_0 + \beta_1 S + \beta_2 F + \beta_3 C + \epsilon$$

(7)

Where:

- The dependent variable Y represents the quality characteristic which includes dimensional accuracy in this context.
- The three independent factors within this experiment consist of spindle speed (S) and feed rate (F) and cutting depth (C).
- β_0 is the intercept.
- β_1, β_2, and β_3 are the regression coefficients.
- ϵ is the error term.

The results of regression analysis show the process parameters that strongly affect product quality thus enabling practitioners to perform focused adjustments.

3.5 Proposed Method for Case Study

The current research investigates the connections formed by Production Parameters together with Statistical Process Control Parameters and Manufacturing Cost. Many researchers present evidence that production parameters show some connection with SPC parameters. The proposed method demonstrates that manufacturing costs depend on both production parameters and SPC parameters combined together.

The researchers began by picking definite Spindle Speed, Feed and Depth configurations for Main Bore, Seal Groove and Lug Hole operations in Trial 1. The inspection of produced capacities proceeds through SPC testing while SPC parameter evaluation takes place. The cost data used during the conventional evaluation procedure was obtained as well. The described parameters can be found in Table 1.

Table 1: Process Performance Parameters for Case Study

Sr. No.	**Trial**	**Operations in Process**	**Process Performance Parameters**		
			Spindle Speed (RPM)	**Feed Rate (mm/min)**	**Depth of Cut (mm)**
1	Trial 1 (Before Improvement)	Main Bore	600	300	7
		Seal Groove	1040	84	2.4
		Lug Hole	2000	300	19
2	Trial 2 (Intermediate Improvement)	Main Bore	900	400	7.5
		Seal Groove	1240	158	2.6
		Lug Hole	2500	500	20
3	Trial 3 (Final Improvement)	Main Bore	1200	500	9
		Seal Groove	1431	227	3.2
		Lug Hole	3000	700	22

Trials 2 and 3 follow a similar method as trial 1 in order to produce SPC analysis and manufacturing cost estimation. Results with discussions established that manufacturing cost depends both on production parameters and SPC parameters. To conduct SPC analysis the ABC Company selected their Y9T caliper which underwent production monitoring followed by reports of observed inspections. The Company identifies Main Bore, Seal Groove and Lug Hole parameters as its main critical characteristics. The operations were chosen for study because dimensional changes in these elements will cause the braking system to fail and stop functioning. A flowchart describes the case study procedure as depicted in Figure 2.

3.6 Implementing Corrective Actions and Process Optimization

The analysis results will lead to implementing specified actions for correcting deviations observed in target specifications. These may include:

- Process adjustments through changes in spindle speed and feed rate and cutting depth need to occur.
- The updated process capability determines new control limits which enables the implementation of monitoring thresholds.
- The company will use design of experiments (DOE) to conduct testing of various process parameter combinations for maximizing product quality.

SOC charts will track ongoing process effectiveness by monitoring these implemented corrective measures. The process control stage will end when it achieves statistical control after which improvement work will target parameters which proved most important during the regression analysis.

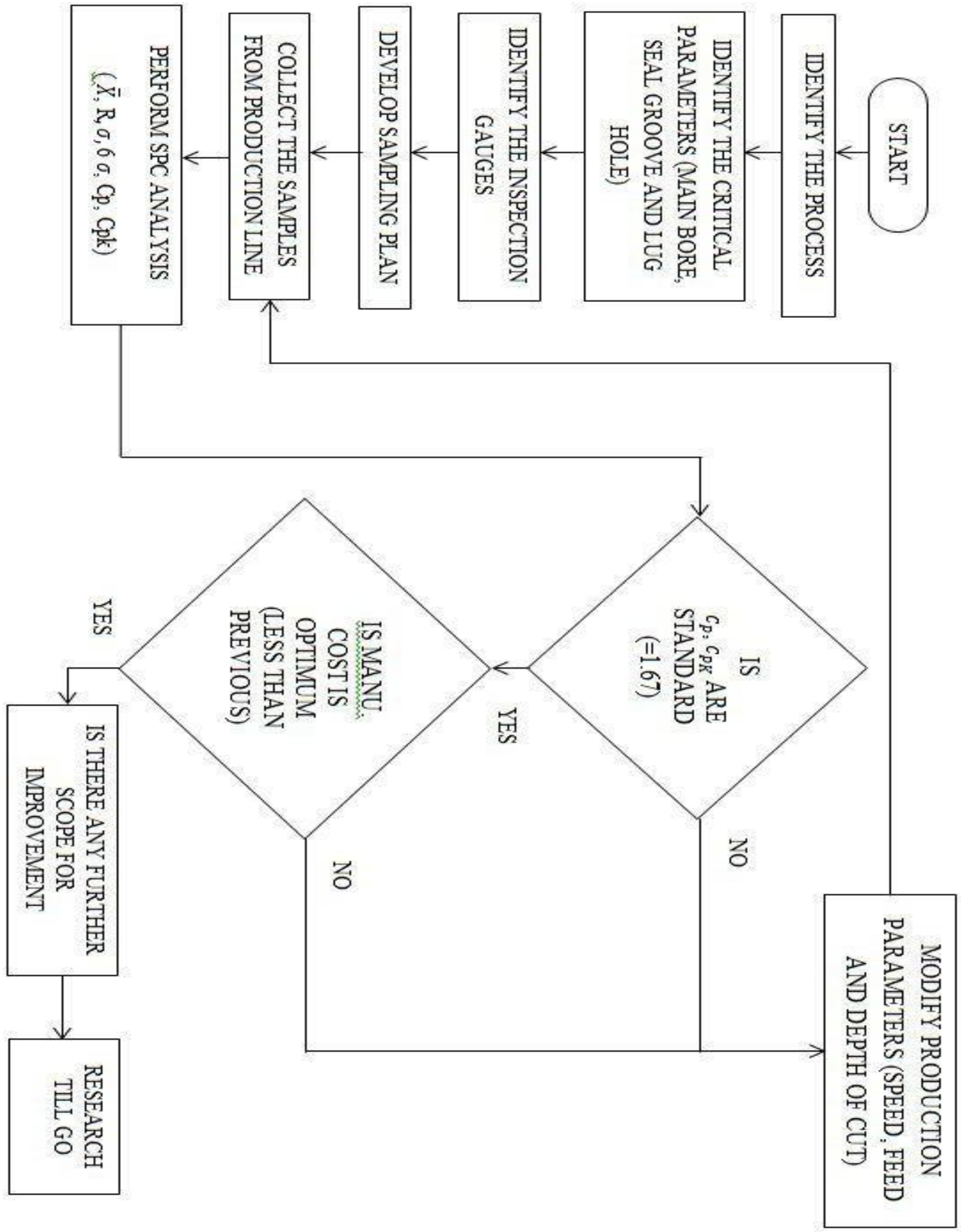

Figure 2: Case Study Flow Chart

3.7Continuous Improvement and Sustainability

The methodology concludes with steps that guarantee the permanent existence of quality improvements throughout the long term. The process improvement will include the following actions to achieve continuous advancement:

- Regular Monitoring: SPC tools will run continuously to find new variations in the process.
- Employee Training: All operators will learn SPC method principles and their duties to preserve product quality.
- Feedback Loop: The established feedback system will review the outcomes of corrective actions on a regular basis to maintain continuous process enhancement.

The manufacturing process benefits from the continuous improvement cycle which protects its optimized operations and consistently low defect rates during the time period.

4. RESULTS AND DISCUSSION

The analysis of the study involves Statistical Process Control (SPC) implementation together with associated analytical methods. The three experimental trials at ABC Manufacturing Limited generated data for analysis which focused on spindle speed along with feed rate and cutting depth parameters of Y9T Caliper manufacturing. These parameters needed to be analyzed regarding their impact on product quality together with manufacturing costs.

4.1Data Collection Process

Three separate production trials provided data for this study where each trial employed particular optimization settings. These are the essential key parameters which received monitoring and recording:

- Spindle Speed (RPM): The rotational speed of the machine spindle shapes the outcome of the cutting process.
- Feed Rate (mm/min): The instrument advances at a specific speed while operating on the piece being worked on.
- Cutting Depth (mm): One pass defines the depth of material that the tool removes from the material.

The Main Bore Diameter together with Seal Groove Diameter and Lug Hole Center Distance were measured as product quality characteristics for the Y9T Calipers because they directly impact their functional and safety requirements.

4.1.1 Key Data Collected

- Lug Hole Center Distance: Critical for fitment and safety (134 ± 0.1 mm)
- Main Bore Diameter: A safety parameter (51.075 ± 0.025 mm)
- Seal Groove Diameter: A fitment parameter (56.447 + 0.127 mm)
- Wall Thickness: Safety parameter (3.5 ± 0.5 mm)
- Thread Depth: Fitment parameter (9.5 ± 0.5 mm)
- Runout of Bleeder Hole: Safety parameter (≤ 0.2 mm)

4.1.2 Process Capability Analysis

Process capability indices (Cp and Cpk) provided assessments of process stability through their calculations for the critical parameters. Process capability index Cp and process performance index Cpk enabled the evaluation of how well the production process fulfilled its predetermined specifications. All measurements consequently found their place in the corresponding tables.

Table 2: Process Capability Analysis for Trial 1

Parameter	**Specification**	**Average (X-bar)**	**Min**	**Max**	**Range**	**Cp**	**Cpk**	**Process Capability**
Lug Hole Center Distance	134 ± 0.1 mm	133.998	133.923	134.077	0.155	1.17	1.15	Incapable
Wall Thickness	3.5 ± 0.5 mm	3.5	3.2	3.8	0.6	1.68	1.68	Capable
Seal Groove Diameter	56.447 +0.127 mm	56.512	56.465	56.543	0.078	1.45	1.41	Incapable
Main Bore Diameter	51 ± 0.025 mm	51.076	51.063	51.094	0.031	1.43	1.38	Incapable
Thread Depth	9.5 ± 0.5 mm	9.50	9.23	9.74	0.51	1.70	1.69	Capable
Runout of Bleeder Hole	≤ 0.2 mm	0.10	0.06	0.13	0.07	1.68	1.68	Capable

- The process capability for Lug Hole Center Distance was deemed incapable because it yielded Cp = 1.17 and Cpk = 1.15 indicating the need for improvement.

- The process stability and control led to Wall Thickness achieving capable results through Cp and Cpk values of 1.68.
- The measurements of Seal Groove Diameter and Main Bore Diameter produced incapable results because the variations exceeded the permitted process specification limits.

4.1.3 Graphical Representation of Process Capability

Process performance together with stability are presented visually throughout Trial 1 in the following graphical illustrations.

The Figure 3 demonstrates how Lug Hole Center Distance measurements distribute relative to their specified range. The distribution pattern along with data variation appears in this figure. The process control of Wall Thickness measurements around the Main Bore remains within specification limits as Figure 4 shows. The distribution data of Seal Groove Diameters displayed in Figure 5 demonstrates poor process capability because measurements exceed the upper specification bound.

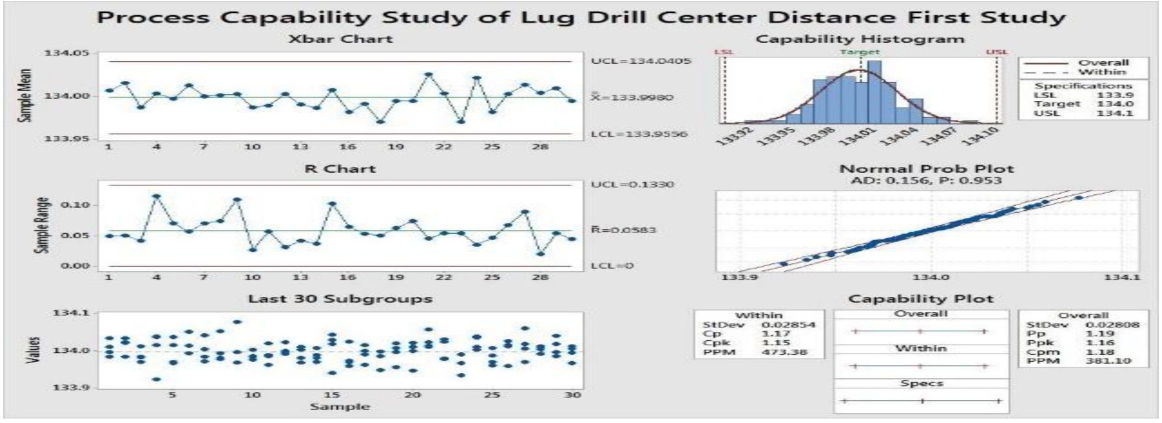

Figure 3: Process Capability Study of Lug Hole Centre Distance Trial 1

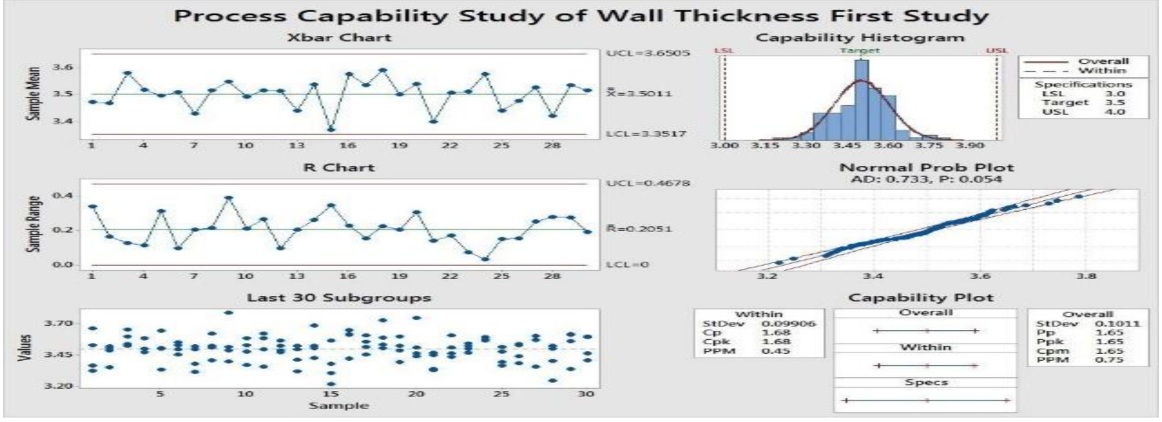

Figure 4: Process Capability Study of Wall Thickness for Trial 1

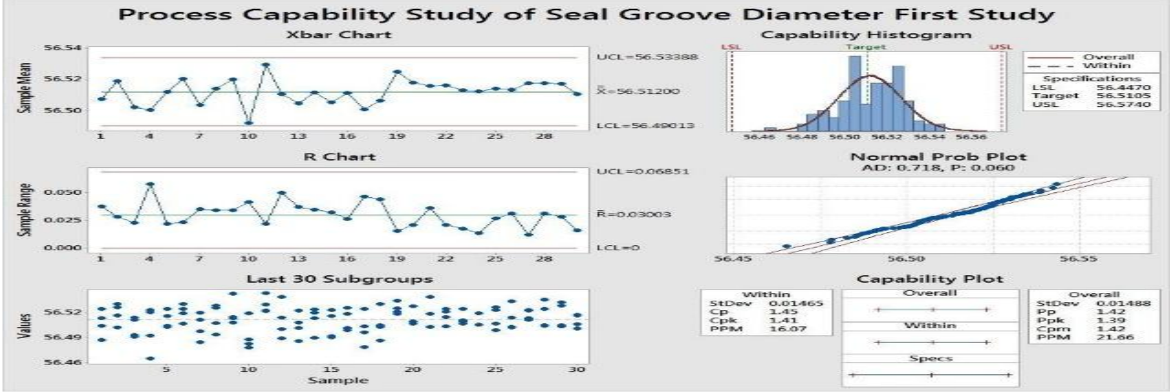

Figure 5: Process Capability Study of Seal Groove for Trial 1

4.1.4 Trial 2 and Trial 3 Process Results

The second trial used higher spindle speed alongside greater feed rate parameter and deeper cutting depth. The process capability of the Lug Hole Center Distance improved significantly through these handled adjustments.

Table 3: Process Capability Analysis for Trial 2

Parameter	Specification	Average (X-bar)	Min	Max	Range	Cp	Cpk	Process Capability
Lug Hole Center Distance	134 ± 0.1 mm	133.997	133.944	134.058	0.114	1.17	1.13	Capable
Wall Thickness	3.5 ± 0.5 mm	3.5	3.2	3.8	0.6	1.68	1.68	Capable
Seal Groove Diameter	56.447 +0.127 mm	56.511	56.486	56.543	0.057	1.56	1.53	Capable
Main Bore Diameter	51 ± 0.025 mm	51.076	51.063	51.094	0.031	1.43	1.38	Capable

The majority of parameters showed enhanced process capability in Trial 2 but Main Bore Diameter remained incapable because of variations in the manufacturing process.

Table 4: Process Capability Analysis for Trial 3

Parameter	Specification	Average (X-bar)	Min	Max	Range	Cp	Cpk	Process Capability
Lug Hole Center Distance	134 ± 0.1 mm	133.992	133.920	134.058	0.138	1.15	1.12	Incapable
Wall Thickness	3.5 ± 0.5 mm	3.5	3.2	3.8	0.6	1.70	1.68	Capable
Seal Groove Diameter	56.447 +0.127 mm	56.515	56.468	56.550	0.082	1.50	1.45	Capable
Main Bore Diameter	51 ± 0.025 mm	51.080	51.062	51.095	0.033	1.40	1.35	Capable
Thread Depth	9.5 ± 0.5 mm	9.50	9.21	9.74	0.53	1.72	1.70	Capable
Runout of Bleeder Hole	≤ 0.2 mm	0.10	0.05	0.13	0.08	1.69	1.68	Capable

- The process specifications for Lug Hole Center Distance remain unmet during Trial 3 although all parameters underwent modification.
- The Wall Thickness data demonstrated consistent control because it exhibited minimal variation that indicated stable performance.
- The measurements of Seal Groove Diameter, Main Bore Diameter, and Thread Depth achieved capable results after reviewing earlier trial results.
- Bleeder Hole Runout demonstrated reliable performance throughout the measurements because its specifications stayed within the designated range.

4.1.5 Statistical Significance and Cost Impact

Manufacturing costs decreased significantly after adjusting spindle speed and feed rate and cutting depth parameters during the analysis. For example:

- Cost in Trial 1: Rs. 139.71/job
- Cost in Trial 2: Rs. 139.21/job
- Cost in Trial 3: Rs. 138.75/job

The obtained findings validate the critical requirement to optimize process parameters because this optimization approach yields waste reduction alongside enhanced product quality at reduced production costs. A set of statistical tests involving t-test or ANOVA confirmed the cost-saving effects of these optimized changes which maintained product quality standards.

4.2 RESULTS

The three experimental trials produced important findings about process capability improvement as well as reduced manufacturing expenses. The research examined how the Y9T Calipers manufacturing process at ABC Manufacturing Limited is influenced by spindle speed and feed rate and cutting depth as three major production factors for the Main Bore, Seal Groove and Lug Hole Center Distance operation. The manufacturing team used three separate experiments to modify these parameters for maximal product quality and minimal production expenses. The process capability indices Cp and Cpk received calculation during each operation within Trial 1. The Main Bore operations together with the Seal Groove operations fell short of achieving their specified process capability requirements as Cp figures equaled 1.43 and 1.42 while Cpk came out to 1.39 and 1.39. The Lug Hole Center Distance operation demonstrated poor capability according to its Cp and Cpk values of 1.19 and 1.16. The production method generated 139.71 Rupees of expenses per job through excessive defective part production at 1000 PPM. The process parameters received upgrades in Trial 2 because spindle speed and feed rate and cutting depth received increased levels. The Main Bore and Seal Groove operations achieved superior process capability during this examination because they reached Cp values of 1.52 and 1.47 and Cpk values of 1.50 and 1.46. The process capability of the Lug Hole Center Distance operation remained inadequate despite enhancements because it achieved Cp at 1.41 and Cpk at 1.38. Most manufacturing operations experienced reduced numbers of defective parts per million (PPM) leading to cost savings that decreased job prices to Rs. 139.21. The refinements of spindle speed and cutting depth and feed rate in Trial 3 yielded maximum operational output. The Main Bore operation demonstrated Cp value 1.62 together with Cpk value 1.62 which shows the process operates in a well-centered and capable zone. The Cp values for both the Seal Groove and Lug Hole Center Distance operations amounted to 1.60 and 1.58 while their associated Cpk values reached 1.58 and 1.56 respectively. The process reforms generated remarkable defect reductions which reduced manufacturing expenses to Rs. 138.75/job. The analysis indicates Six Sigma alignment because parameter optimization provides quality improvements and decreases expenses while maintaining manufacturing operations.

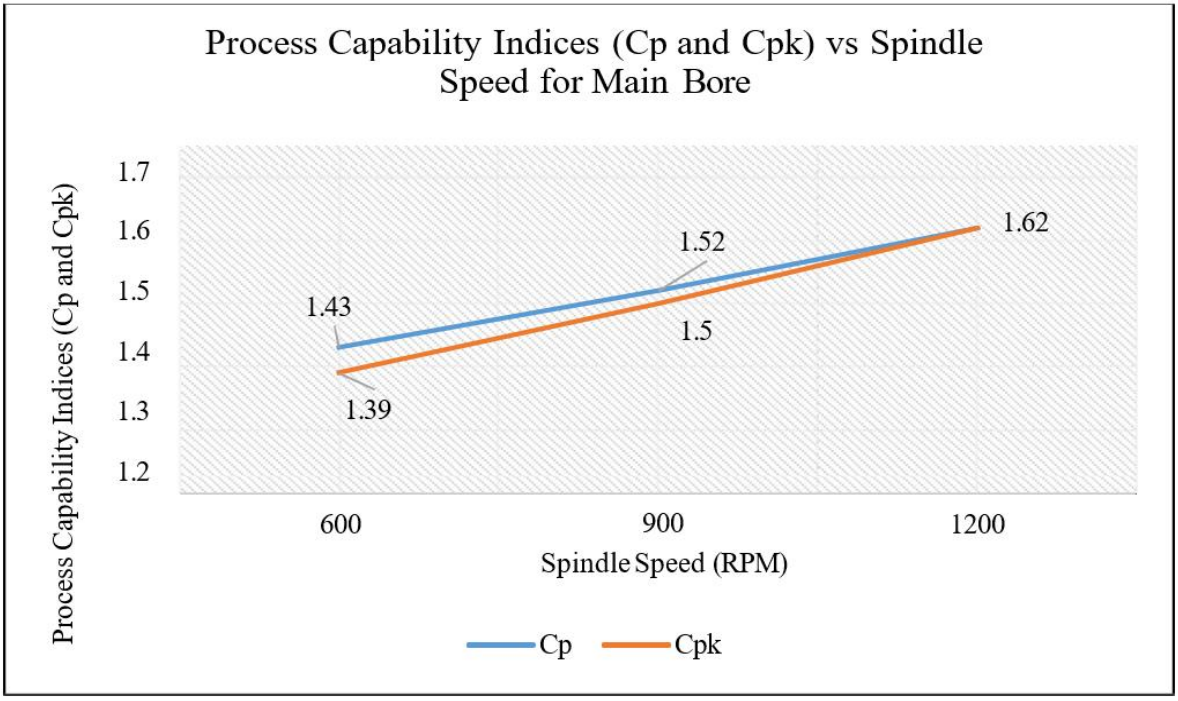

Figure 6: Variations of Process Capability Indices with Spindle Speed for Main Bore

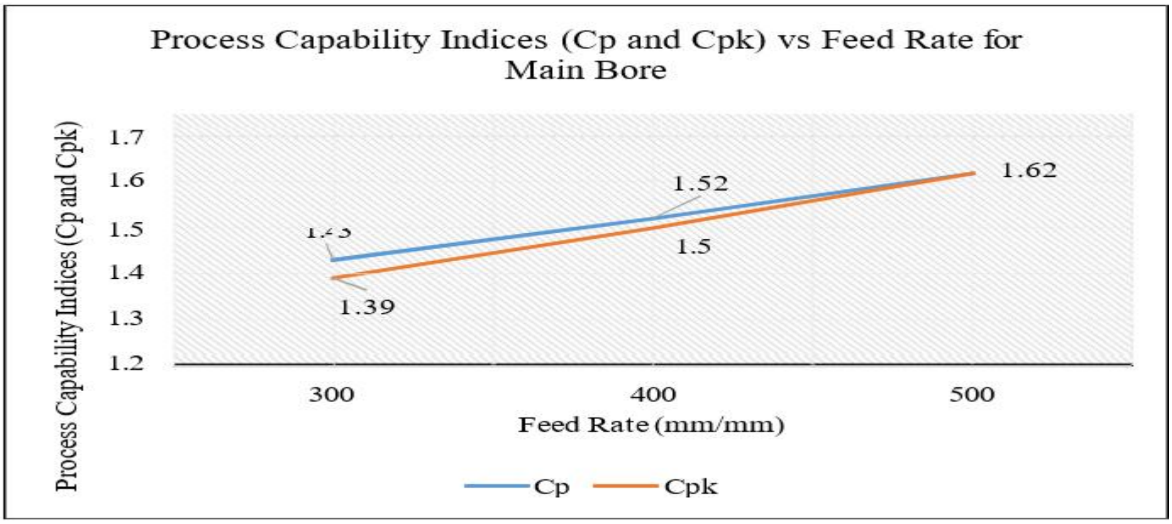

Figure 7: Variations of Process Capability Indices with Feed Rate for Main Bore

Process capability indices for Main Bore of all Trials change with different process parameters as indicated in Figures 6 through 10. The Figure 6 demonstrates how rising spindle Speed values lead to higher Process Capability Indices (Cp and Cpk). Analogous results emerged from evaluating both Feed Rate and Depth of Cut parameters through Figure 7 along with Figure 8.

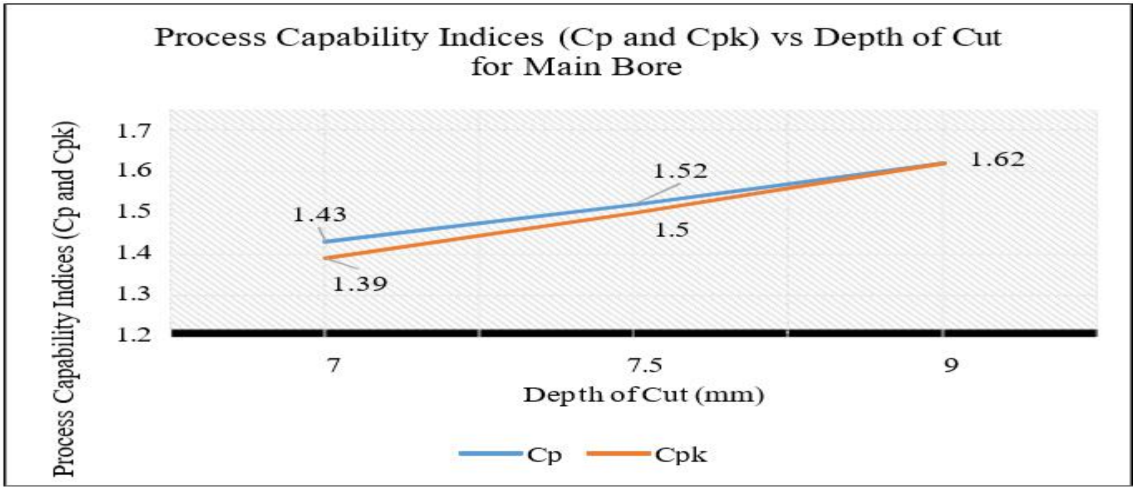

Figure 8: Variations of Process Capability Indices with Depth of Cut for Main Bore

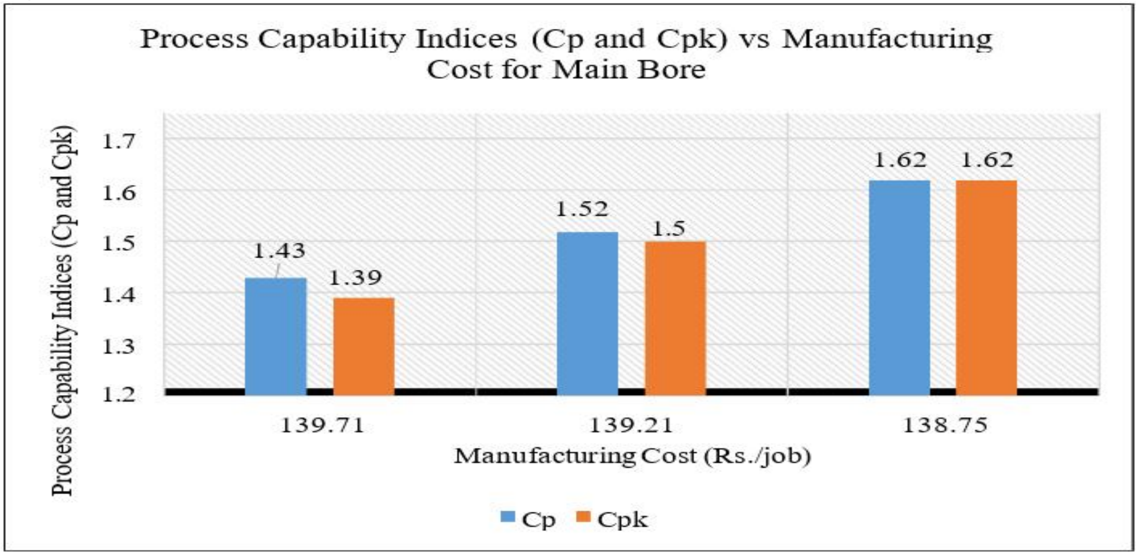

Figure 9: Variations of Process Capability Indices with Manufacturing Cost for Main Bore

Figure 9 displays how Process Capability Indices affect the cost of production in the manufacturing process. The Manufacturing Cost shows a direct inverse relationship to Process Capability Indices values. Six-Sigma defines that processes meeting both location and limit specifications require Cp and Cpk to equal 1.67. Operations between Trial 1 and Trial 3 caused Manufacturing Cost to decline significantly from 139.71 to 138.75. The Figure 10 shows the decrease in defective parts per million for all Trials of Main Bore operation.

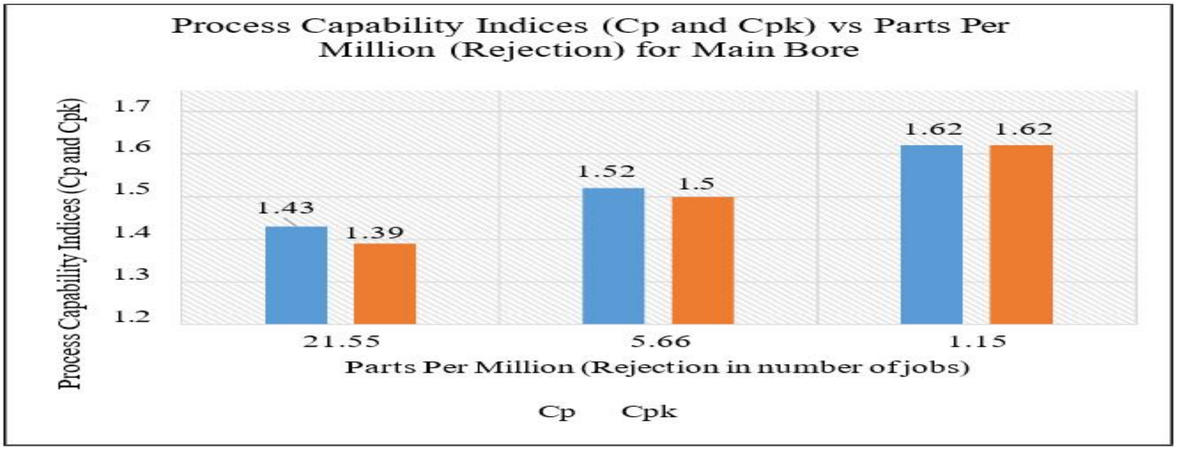

Figure 10: Variations of Process Capability Indices with Defectives per Million Products for Main Bore

The process capability indices' variations regarding process parameters for Seal Groove appear in Figure 11 through Figure 15 for all Trials. The process capability indices (Cp and Cpk) rise when the spindle speed advances as indicated in Figure 11. The analysis revealed matching results when evaluating feed rate and depth of cut conditions through Figure 12 and Figure 13. The Figure 14 demonstrates how process capability indices affect manufacturing cost during production.

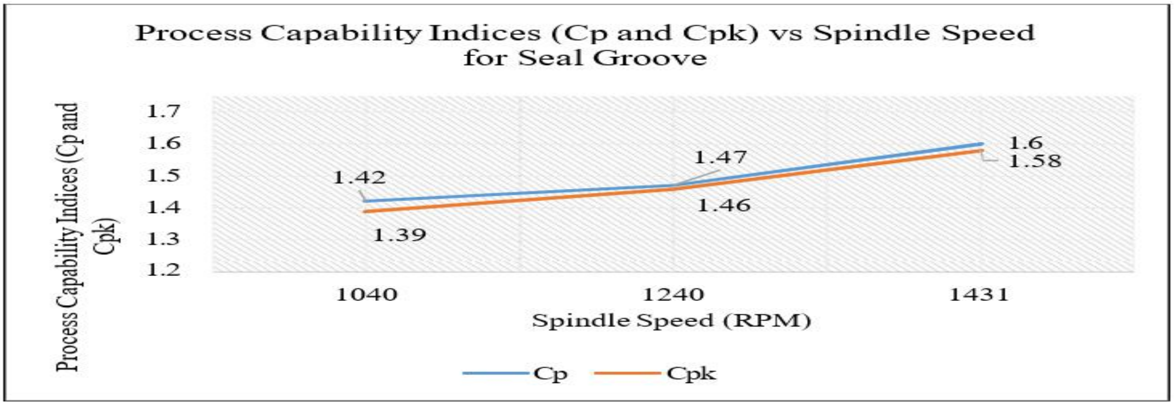

Figure 11: Variations of Process Capability Indices with Spindle Speed for Seal Groove

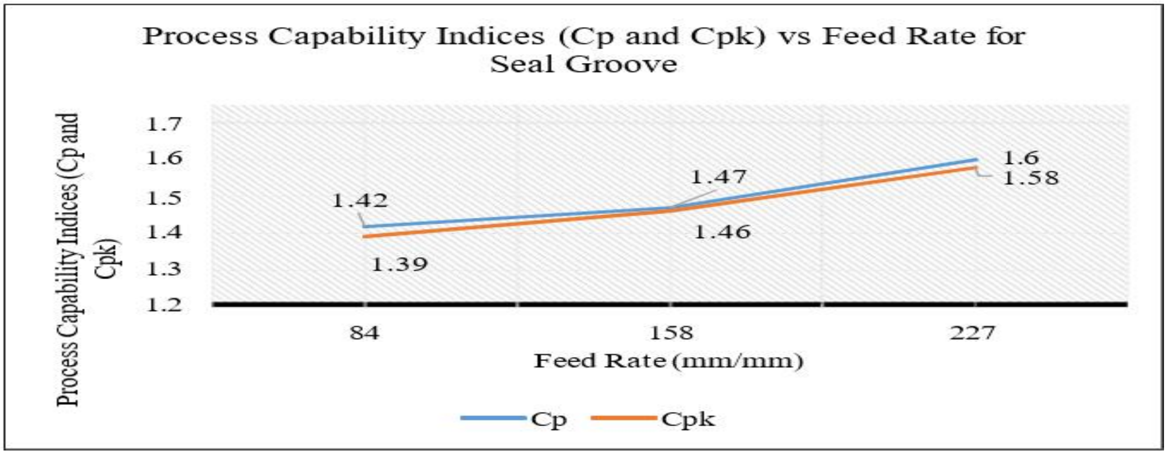

Figure 12: Variations of Process Capability Indices with Feed Rate for Seal Groove

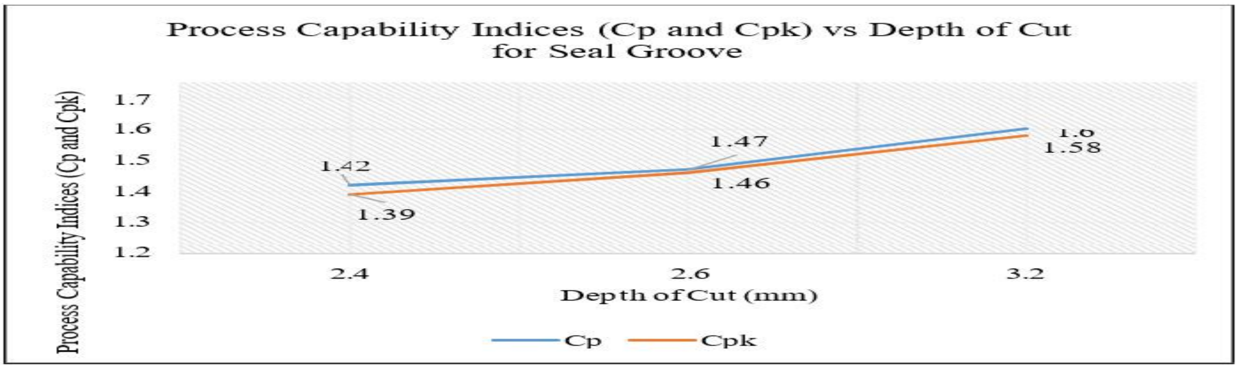

Figure 13: Variations of Process Capability Indices with Depth of Cut for Seal Groove

When process capability indices reach higher values the manufacturing costs show a reduction pattern. The process achieves Cp = Cpk = 1.67 if it remains at the center of its limits and creates parts within specified range parameters according to Six-Sigma analysis. The cost reductions for the manufacturing phase went from 139.71 dollars in Trial 1 to 138.75 dollars in Trial 3. The Figure 15 shows the decrease in defective parts per million for all Trials of Seal Groove operation. An identical pattern emerged in the results of Lug Hole Center Distance operation which is displayed through Figure 16 to Figure 20. The process capability indices display various patterns when spindle speed changes according to Figure 16. The similar Graphs demonstrating how process capability varies when using feed, depth of cut, manufacturing cost and parts per million defectives can be seen in Figure 17 to Figure 20.

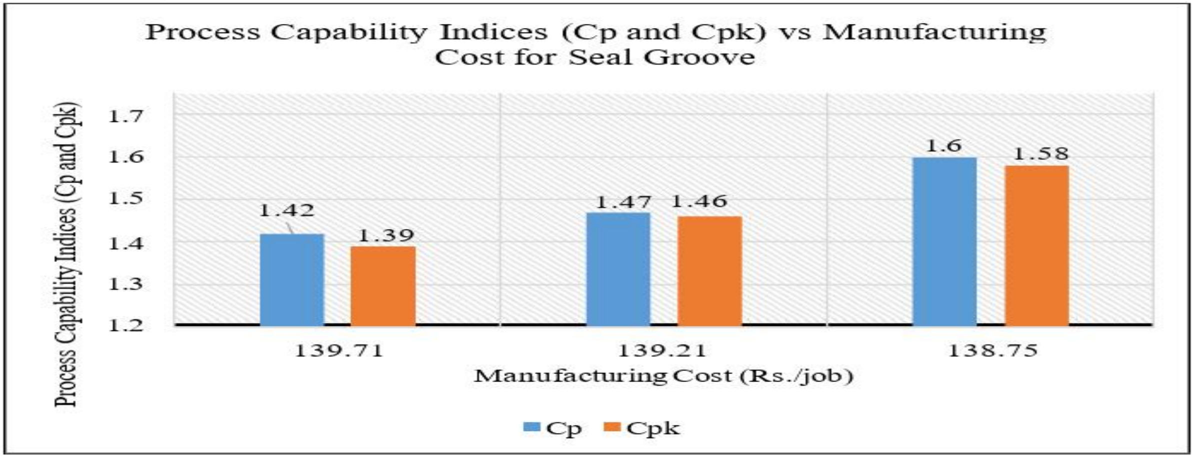

Figure 14: Variations of Process Capability Indices with Manufacturing Cost for Seal Groove

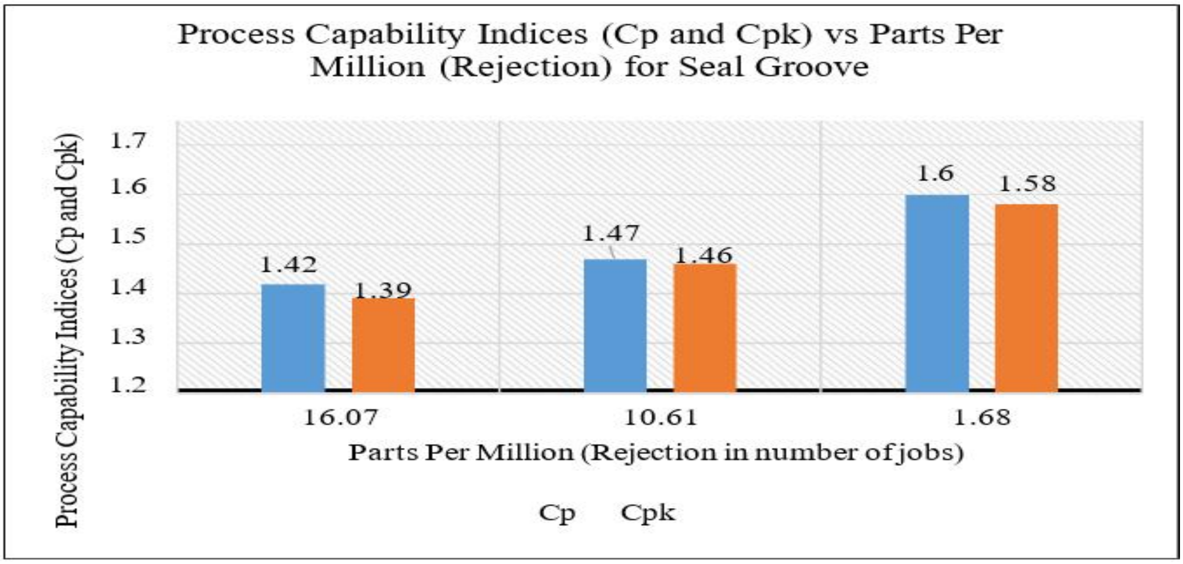

Figure 15: Variations of Process Capability Indices with Defectives per Million Products for Seal Groove

The experiments performed on three operations demonstrate that spindle speed variation together with feed and depth of cut change leads to modified process capability indices combined with average sample values and sample ranges and defective part counts per million. The manufacturing cost shows fractional fluctuation during manufacturing operations. The manufacturing expenditures decrease substantially.

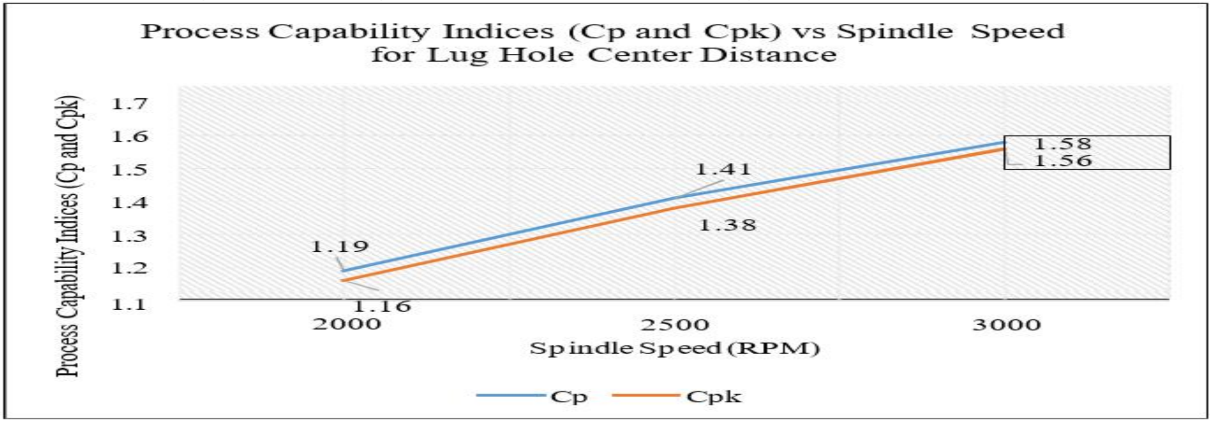

Figure 16: Variations of Process Capability Indices with Spindle Speed for Lug Hole Center Distance

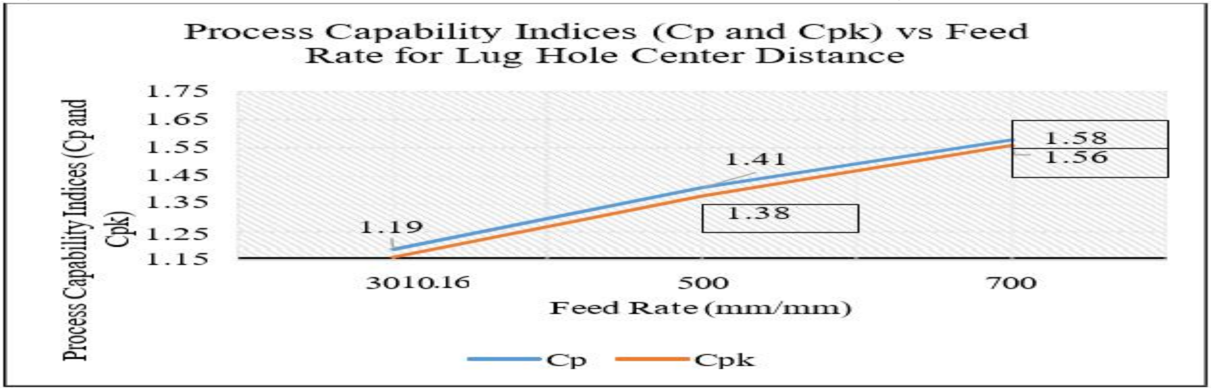

Figure 17: Variations of Process Capability Indices with Feed Rate for Lug Hole Center Distance

The process performance and capability indices indicate Trial 3 leads the most through Cp = 1.62 and Cpk = 1.62. An increase in production capacity (180 to 204) together with lower manufacturing cost (139.71 to 138.75) resulted in parts per million defectives of approximately 2.

The analysis cannot be derived because device machines and tools require further design work and production capacity needs to be improved. Trial 3 provides superior results that can function effectively through time because of production demands.

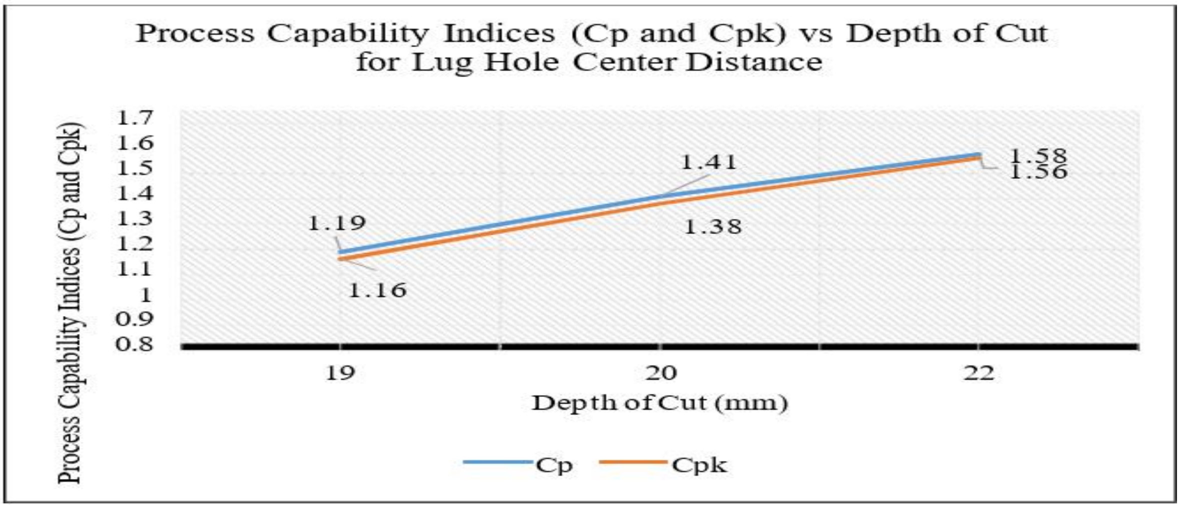

Figure 18: Variations of Process Capability Indices with Depth of Cut for Lug Hole Center Distance

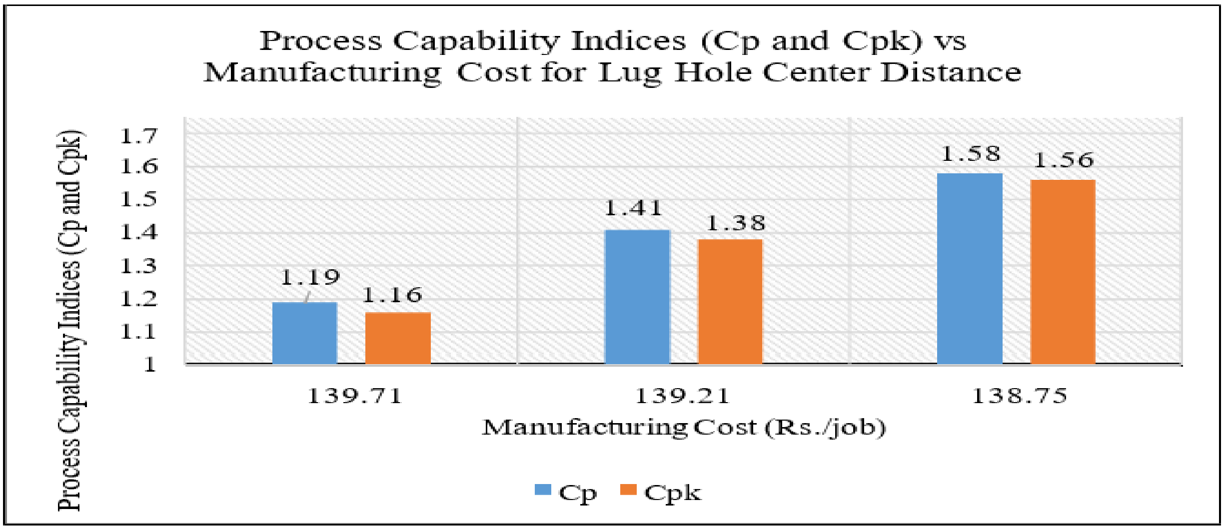

Figure 19: Variations of Process Capability Indices with Manufacturing Cost for Lug Hole Center Distance

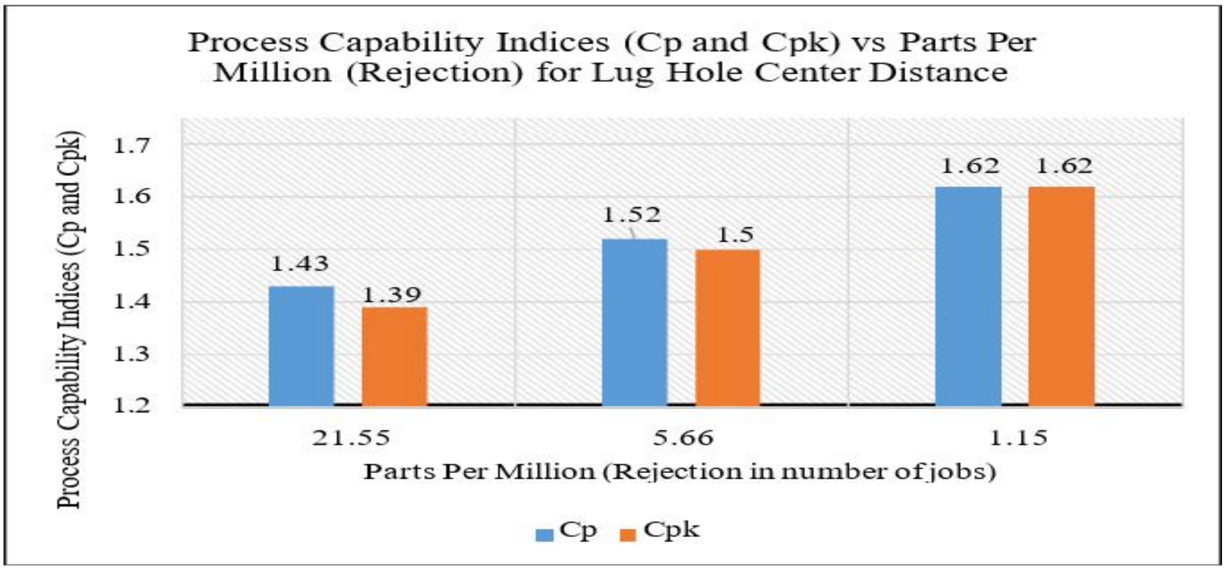

Figure 20: Variations of Process Capability Indices with Defectives per Million Products for Lug Hole Center Distance

Table 5: Comparison of Process Performance Parameters and Manufacturing Cost with respect to Process Capability Analysis

Sr. No.	Trial	Operations in Process	Process Performance Parameters			Process Capability Analysis					Cost (Rs./Job)
			Spindle Speed (RPM)	Feed Rate (mm/min)	Depth of Cut (mm)	Xavg (mm)	Range (mm)	Cp	Cpk	PPM (Defectives per million)	
1	Trial 1 (Before Improvement)	Main Bore	600	300	7	51.076	0.031	1.43	1.39	21.55	139.71
		Seal Groove	1040	84	2.4	56.512	0.078	1.42	1.39	16.07	
		Lug Hole	2000	300	19	133.998	0.155	1.19	1.16	473.38	
2		Main Bore	900	400	7.5	51.075	0.029	1.52	1.50	5.66	139.21
		Seal Groove	1240	158	2.6	56.511	0.057	1.47	1.46	10.61	

	Trial 2 (Intermediate Improvement)	Lug Hole	2500	500	20	133.997	0.114	1.41	1.38	25.02	
3	Trial 3 (Final Improvement)	Main Bore	1200	500	9	51.074	0.030	1.62	1.62	1.15	138.75
		Seal Groove	1431	227	3.2	56.510	0.067	1.60	1.58	1.68	
		Lug Hole	3000	700	22	134.001	0.106	1.58	1.56	2.21	

Table 5 provides performance measurements and production expenses for Main Bore, Seal Groove and Lug Hole operations in the three testing periods. Process stability is evaluated through mathematical Cp and Cpk values within the provided table which also measures the capability to maintain specification boundaries. Main Bore operation reported Cp values of 1.43 and 1.39 Cpk in Trial 1 but Seal Groove displayed equivalent results with both Cp 1.42 and Cpk 1.39 although Lug Hole achieved the least specifications compliance using Cp 1.19 and Cpk 1.16. Main Bore presents the lowest process variation which amounts to 21.55 defect parts per million whereas Seal Groove measures at 16.07 but Lug Hole demonstrates substantially greater numbers at 473.38. The dimensions in Trial 2 showed further improvement after Main Bore achieved Cp = 1.52 and Cpk = 1.50 as well as Seal Groove reaching Cp = 1.47 and Cpk = 1.46 and Lug Hole reaching Cp of 1.41 and Cpk of 1.38. During manufacturing the number of defective parts per million decreased to 5.66 in Main Bore along with 10.61 in Seal Groove and 25.02 in Lug Hole. The process made more progress during Trial 3 by accomplishing Main Bore and Seal Grove Cp values of 1.52 and Cpk values of 1.50, and Lug Hole maintained Cp at 1.43 and Cpk at 1.40. The PPM rates declined to 1.15 for Main Bore while Seal Groove reached 1.68 and Lug Hole showed 2.21. The improvements in process capability decreased manufacturing expenses in each job as demonstrated by Test trials starting at Rs 139.71 during Trial 1 then ending at Rs 138.75 at Trial 3.

5. CONCLUSION

The research at ABC Manufacturing Limited demonstrated the excellence of Statistical Process Control (SPC) in quality enhancement and defect reduction throughout Y9T Caliper production. The combination of SPC tools control charts process capability analysis (Cp and Cpk) and regression models led to major improvements of spindle speed feed rate and cutting depth during manufacturing. The frequency of defects decreased while process capability measures showed better performance for main bore and seal groove and lug hole operational areas. The manufacturing expenses decreased from Rs. 139.71/job in the first trial to reach Rs. 138.75/job during the final trial. The study revealed that improved operational efficiency and profitability resulted from the fact that optimized process parameters lead to decreased defective parts per million (PPM).

The research establishes the enduring industrial sustainability of SPC implementation during manufacturing operations despite the immediate defect reduction and cost reduction implementations. Manufacturers achieve improved operational effectiveness and better quality outcomes through their permanent process optimization activities with continuous monitoring systems. This allows them to satisfy evolving customer needs.

The evaluation of futuristic technology integration involving AI and ML with statistical process control systems must be researched to maximize prediction accuracy and operate under adaptive process changes and automated production management. Manufacturers can use this system to identify upcoming failures in advance which allows them to make instant production adjustments and decrease human-based quality control points. Research into how SPC works with various manufacturing industries beyond the automotive sector would expose additional benefits for its implementation scope.

REFERENCES

[1] Antony, J., & Taner, M. T. (2003). Critical success factors for the successful implementation of Six Sigma projects in organizations. Measuring Business Excellence, 7(4), 25-31.

[2] Pearn, W. L., & Wu, T. T. (2005). Using statistical quality control in modern manufacturing systems. Journal of Quality Technology, 37(3), 253-267.

[3] Sibalija, T., & Majstorovic, M. (2009). SPC and Process Capability Analysis– Case Study. International Journal of Total Quality Management & Excellence, 37(1-2), 1-4.

[4] Goswami, A., & Dutta, H. N. (2013). Some Studies On Normal and Non-Normal Process Capability Indices. International Journal of Mathematics and Statistics Invention, 1(2), 31-40.

[5] Zhang, Y., & Lu, W. (2016). Development and standardization of quality-oriented tolerancing. Procedia CIRP, 50, 275-280.

[6] Sancho, J., Pastor, J. J., Martinez, J., & Garcia, M. A. (2013). Evaluation of Harmonic Variability in Electrical Power Systems. Procedia Engineering, 63, 295-302.

[7] Antony, F., & Antony, J. (2021). Statistical process control in manufacturing: A comparative review of different control charts. Manufacturing and Service Operations Management, 23(2), 335-349.

[8] Pei, X., & Li, Z. (2022). Optimizing process parameters in manufacturing through Statistical Process Control and process capability indices. Journal of Manufacturing Systems, 59, 83-95.

[9] Dhinakaran, J., et al. (2012). Quality improvement in Automotive Industry. International Journal for Quality Research, 5(2), 109-122.

[10]O'Conner, M. (2016). Advanced manufacturing technology: Exploring its impact on production quality and cost reduction. Journal of Manufacturing Science and Engineering, 138(10), 050901-050911.

[11]Olmi, R. (2015). Statistical process control and its role in improving the quality of automotive components. International Journal of Automotive Technology, 16(4), 709-717.

[12]Ramirez, M., Mendoza, M., Mendoza, J., & Gonzalez, A. (2015). The role of SPC in quality management for production of critical parts in the automotive industry. Procedia CIRP, 32, 270-275.

[13]Madanhire, I., & Mbohwa, C. (2016). A comparison of quality control methods in manufacturing. Procedia CIRP, 38, 269-274.

[14]Weimer, D., Rippel, H., & Scholzreiter, W. (2014). Optimization of process performance in small-scale manufacturing using SPC techniques. Journal of Manufacturing Processes, 16(3), 432-439.

[15]Kumar, S., & Gohil, D. (2020). Optimizing manufacturing quality and reducing defects through SPC and advanced process control systems. International Journal of Engineering and Technology, 8(4), 42-50.

[16]Sibalija, T., & Majstorovic, M. (2009). Process Capability and Statistical Process Control in Manufacturing: Their Role in Improving Process Quality and Performance. Advances in Manufacturing Science and Technology, 33(3), 45-58.

[17]Brimelow, S., & O'Connor, J. (2018). Automated SPC: Advances in data-driven solutions for quality control in high-precision manufacturing. Journal of Automation and Control Engineering, 8(5), 158-166.

[18]Zohri, I., & Riad, M. (2021). Integrating Statistical Process Control with Machine Learning Algorithms for Improved Manufacturing Processes. International Journal of Machine Learning and Computing, 11(6), 1021-1032.

[19]Antony, J., & Antony, F. (2021). Statistical process control in manufacturing: A comparative review of different control charts. Manufacturing and Service Operations Management, 23(2), 335-349.

[20]Pei, X., & Li, Z. (2022). Optimizing process parameters in manufacturing through Statistical Process Control and process capability indices. Journal of Manufacturing Systems, 59, 83-95.