Center for Management Science Research
ISSN: 3006-5291 3006-5283
Volume 4, Issue 6, 2026

THE IMPACT OF QUALITY CONTROL STRATEGIES ON MEASUREMENT PROCESS OPTIMIZATION AND OPERATIONAL PERFORMANCE: A CASE STUDY IN AUTOMOTIVE MANUFACTURING

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DOI: https://doi.org/10.5281/zenodo.21192395

Keywords
Quality Control Strategies; Measurement Process Optimization; Statistical Process Control; Manufacturing Performance; Continuous Improvement; Operational Excellence; Precision Manufacturing.

Article History
Received: 25 April 2026
Accepted: 04 June 2026
Published: 21 June 2026

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Abstract

*Maintaining accurate and reliable measurement systems is essential for ensuring product quality and operational excellence in precision manufacturing industries. This study investigates the impact of quality control strategies on measurement process optimization and manufacturing performance through a case study conducted in an automotive component manufacturing environment. The research employed a quantitative case study approach using production records, Measurement System Analysis (MSA), Gauge Repeatability and Reproducibility (Gauge R&R), Statistical Process Control (SPC), Pareto analysis, Fishbone analysis, scatter diagrams, and process capability analysis to identify measurement-related challenges and evaluate the effectiveness of corrective actions. The findings revealed that measurement system deficiencies, including overdue instrument calibration, inadequate operator competency, lack of standardized measurement procedures, and environmental variations, were the primary contributors to process instability and product rejection. Following the implementation of integrated quality control strategies comprising calibration system enhancement, standardized operating procedures, environmental control, operator training, and continuous SPC monitoring, substantial improvements were achieved across key operational indicators. The process capability index (Cpk) increased from **0.61 to 1.58**, Gauge R&R improved from **41.1% to 11.8%**, the rejection rate decreased from **4.8% to 0.6%**, monthly customer complaints declined by **85.3%**, and quality-related costs were reduced by approximately **81.3%**, resulting in estimated annual savings of **PKR 37 million**. These findings demonstrate that systematic quality control strategies significantly enhance measurement process reliability, improve production performance, and support continuous improvement in manufacturing organizations. The study provides practical guidance for production managers and quality professionals seeking to strengthen operational performance through structured quality management practices and evidence-based decision-making.*

1 Introduction:

Global manufacturing industries are undergoing rapid technological transformation driven by increasing customer expectations, globalization, digital manufacturing, and the adoption of Industry 4.0 technologies. Organizations operating in highly competitive markets are continuously seeking strategies to improve product quality, minimize production costs, and achieve operational excellence [1-2]. Among the various determinants of manufacturing performance, measurement accuracy occupies a critical position because every production decision ultimately depends upon reliable inspection data. An effective measurement system not only verifies product conformity but also provides essential information for process control, quality assurance, and continuous improvement. Precision manufacturing industries such as automotive, aerospace, medical device production, and defense manufacturing operate within extremely stringent dimensional and geometric tolerances. Components including crankshafts, connecting rods, transmission gears, camshafts, suspension assemblies, and engine blocks require dimensional accuracies often within ±0.01 mm to ±0.05 mm. [3-4]. Even minor deviations in measurement accuracy may result in the acceptance of defective components or the rejection of conforming products, leading to increased manufacturing costs, customer dissatisfaction, warranty claims, production delays, and reduced organizational competitiveness.

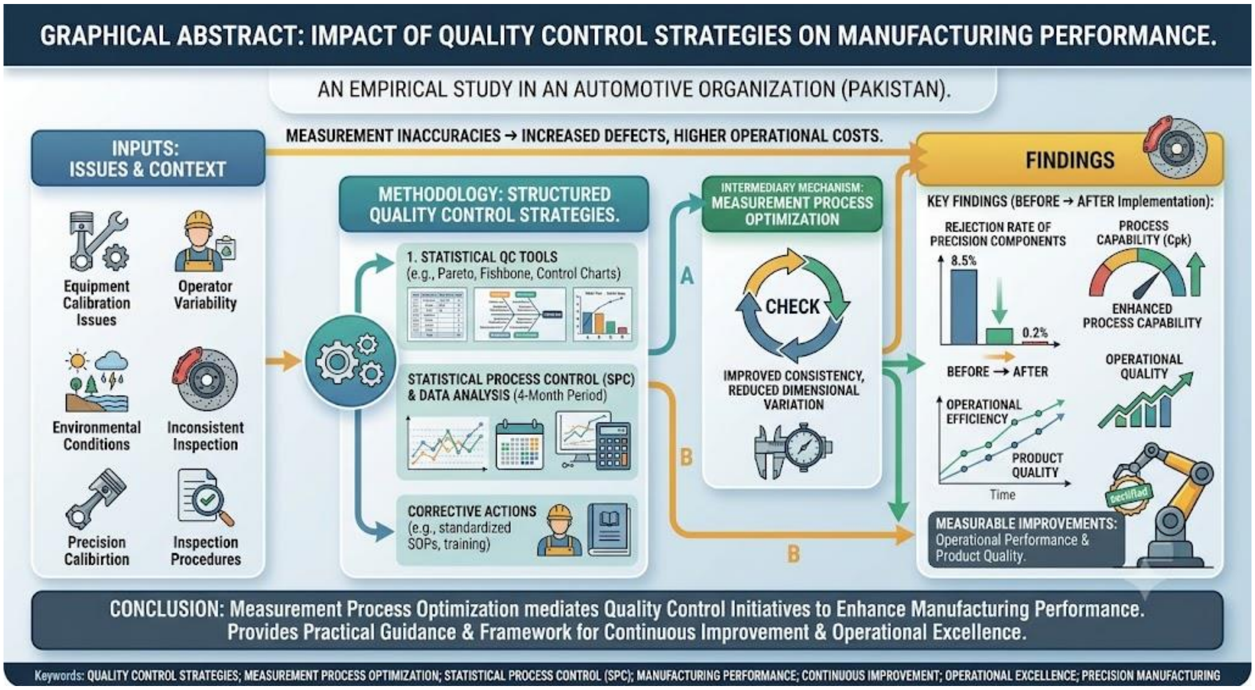


Figure 1. Visual Abstract of Research Work

In modern manufacturing systems, quality is no longer viewed solely as the responsibility of the inspection department but rather as an integrated organizational philosophy encompassing production planning, process control, employee competence, equipment maintenance, supplier quality, and customer satisfaction [5]. Consequently, organizations increasingly rely on comprehensive quality control strategies that combine statistical quality control techniques with standardized operating procedures, preventive maintenance, calibration management, continuous monitoring, and employee training. These strategies facilitate early detection of process deviations, minimize measurement uncertainty, and support evidence-based decision-making throughout the production cycle. Despite significant technological advancements in Coordinate Measuring Machines (CMMs), digital metrology systems, laser scanners, and automated inspection technologies, many manufacturing organizations continue to experience quality losses arising from inconsistent measurement practices. Factors such as inadequate calibration schedules, environmental fluctuations, worn measuring instruments, operator-induced variability, insufficient training, and the absence of standardized inspection procedures frequently compromise measurement reliability [6]. These deficiencies increase process variation and reduce process capability, ultimately affecting manufacturing performance and organizational profitability. Quality control strategies provide a systematic framework for addressing these challenges by integrating preventive, detective, and corrective quality management practices. Statistical Process Control (SPC), Pareto Analysis, Fishbone Diagrams, Histograms, Check Sheets, Scatter Diagrams, Control Charts, and Process Capability Analysis enable organizations to identify root causes of quality problems, monitor process stability, and implement data-driven improvement initiatives [7]. The successful integration of these techniques promotes continuous improvement while reducing production variability and the cost of poor quality. This research investigates the effectiveness of quality control strategies in optimizing measurement processes and improving operational performance within the automotive manufacturing industry. The study employs an empirical case study approach using production and quality assurance records from a leading automotive manufacturing organization in Pakistan. The selected organization manufactures precision engine and transmission components where dimensional accuracy is essential for ensuring product functionality, reliability, and customer safety. During the study period, the organization experienced a noticeable increase in production rejections associated with measurement inconsistencies, providing an opportunity to evaluate the effectiveness of structured quality improvement interventions. The study focuses on identifying the major sources of measurement variability through the application of statistical quality control tools. Root causes are systematically analyzed using Pareto Analysis, Fishbone Diagrams, Check Sheets, Histograms, and Statistical Process Control techniques. Based on the identified deficiencies, corrective actions including calibration improvement, operator competency enhancement, inspection standardization, and preventive maintenance are implemented under the Plan–Do–Check–Act (PDCA) continuous improvement framework. Process performance before and after implementation is compared to assessing the effectiveness of the proposed quality control strategies. Unlike many previous studies that primarily examine individual quality tools in isolation, this research develops an integrated quality management framework that combines measurement process optimization, statistical quality control techniques, and continuous improvement principles to enhance operational performance. The study therefore bridges the gap between engineering quality management and strategic operational improvement by demonstrating how measurement reliability contributes directly to organizational performance.

The findings are expected to provide practical guidance for manufacturing managers, quality engineers, production supervisors, and industrial practitioners seeking to reduce production variability, improve measurement reliability, strengthen quality assurance systems, and achieve sustainable manufacturing excellence. Furthermore, the study contributes to the existing literature by providing empirical evidence regarding the relationship between quality control strategies, measurement process optimization, and operational performance within the context of precision manufacturing industries in developing economies.

1.1 Research Objectives

1. To evaluate the effectiveness of existing measurement processes in precision manufacturing.
2. To identify the principal causes of measurement variability using statistical quality control techniques.
3. To examine the impact of quality control strategies on measurement process optimization.
4. To evaluate the influence of optimized measurement processes on operational performance.
5. To develop a continuous improvement framework for sustainable quality enhancement in
6. manufacturing organizations.

1.2 Research Hypotheses

H1: Quality control strategies significantly improve measurement process optimization.

H2: Measurement process optimization significantly improves operational performance.

H3: Quality control strategies significantly improve operational performance.

H4: Measurement process optimization mediates the relationship between quality control strategies and operational performance.

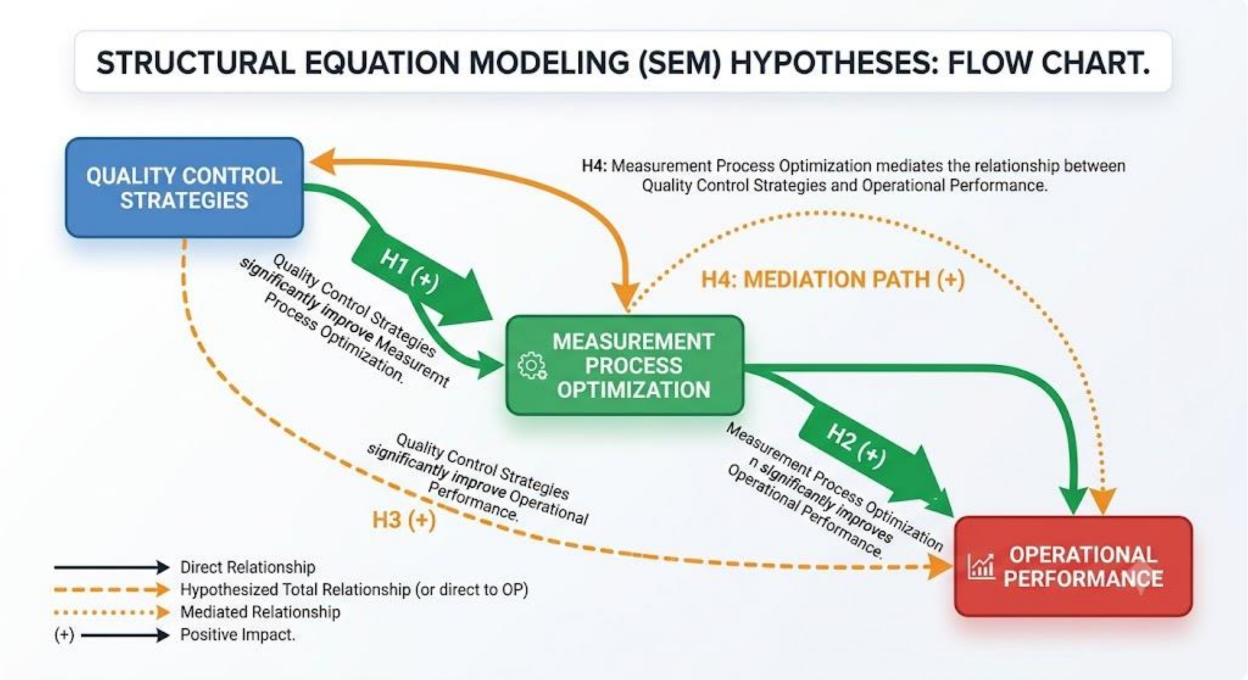


Figure 2. Hypothesis Flow Chart

2. Literature Review:

2.1 Quality Control Strategies in Manufacturing

Quality has become a strategic driver of competitiveness in modern manufacturing rather than merely an inspection activity. Organizations increasingly recognize that sustainable manufacturing performance depends on systematic quality control strategies integrated throughout the production process. These strategies include statistical quality control (SQC), Statistical Process Control (SPC), standardized operating procedures (SOPs), preventive maintenance, calibration management, operator competency development, and continuous monitoring [8]. The objective is to minimize process variability, reduce defects, and improve customer satisfaction.

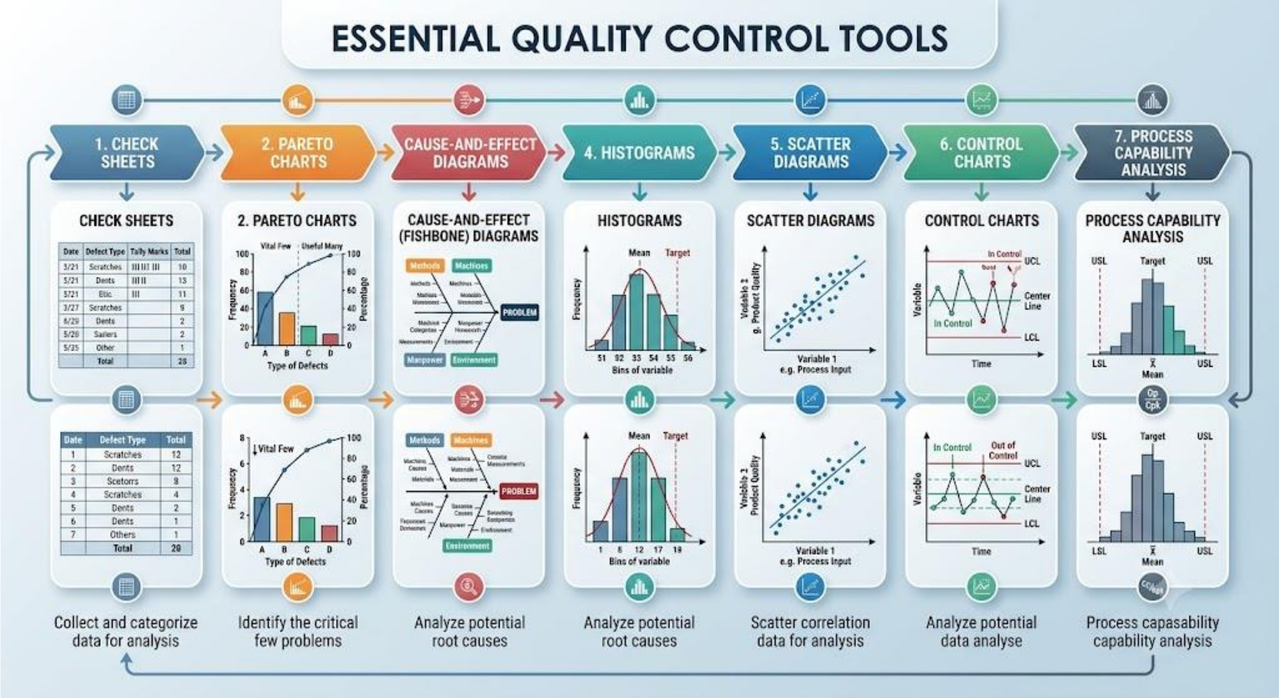
The emergence of Industry 4.0 has further transformed quality management by integrating automation, digital metrology, machine learning, and real-time monitoring into production systems. Modern quality control therefore extends beyond end-product inspection toward predictive and preventive approaches that continuously monitor process capability and detect deviations before defective products are produced. Recent studies have highlighted that intelligent quality control systems improve productivity while simultaneously reducing waste, rework, and quality-related costs [9-10].

2.2 Measurement Process Optimization

Measurement is one of the most critical elements of manufacturing quality assurance because production decisions are entirely dependent upon accurate inspection results. In precision manufacturing industries such as automotive, aerospace, and medical device production, measurement uncertainty directly influences product conformity and process capability. Measurement process optimization refers to systematic improvements in measurement accuracy, repeatability, reproducibility, calibration, environmental control, and inspection standardization. A reliable measurement system reduces false acceptance and false rejection of products while supporting effective process control. Measurement System Analysis (MSA) has become a fundamental practice for evaluating gauge performance [11]. Gauge Repeatability and Reproducibility (Gauge R&R), bias analysis, linearity, and stability assessments help organizations determine whether measurement variation originates from the measuring equipment or from the manufacturing process itself. Studies consistently demonstrate that organizations investing in robust measurement systems experience lower defect rates and improved operational efficiency.

2.3 Statistical Quality Control Tools

Statistical Quality Control (SQC) provides scientific techniques for analyzing process variation and identifying sources of quality problems. Rather than relying solely on final inspection, SQC emphasizes continuous monitoring of manufacturing processes using statistical evidence [12-14].



Date	Defect Type	Tally Marks	Total
3/21	Scratches	IIII III III	10
5/21	Dents	IIII II	13
5/21	Etic	III	11
3/27	Scratches		9
6/29	Dents		2
5/28	Sailers		2
5/35	Other		1
	Total		28

Date	Defect Type	Total
1	Scratches	12
2	Dents	12
3	Scetorrs	8
4	Scratches	4
5	Dents	2
6	Dents	1
7	Others	1
	Total	20

Figure 3. Quality Control Strategies

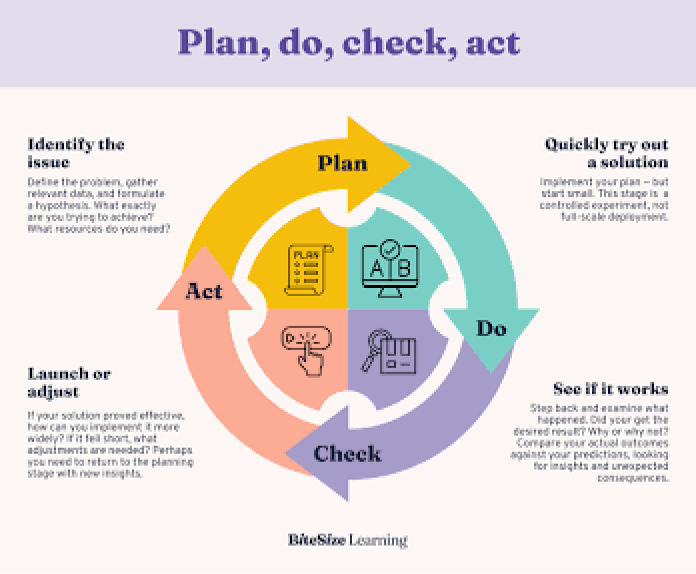
Pareto analysis assists organizations in identifying the "vital few" causes responsible for most production defects, thereby enabling efficient allocation of improvement efforts. Fishbone diagrams facilitate systematic investigation of potential causes associated with manpower, machinery, methods, materials, measurement, and environmental conditions. Histograms visualize process distributions and variation, while control charts distinguish between common-cause and special-cause variation. Control charts remain one of the most effective tools for maintaining process stability. When process observations remain within statistically determined control limits, the process is considered stable. Conversely, points outside the limits indicate assignable causes requiring immediate corrective action [15-16]. Process capability indices such as Cp and Cpk further evaluate whether manufacturing processes consistently meet engineering specifications.

2.4 Continuous Improvement through the PDCA Cycle

Continuous improvement is a fundamental principle of Total Quality Management (TQM) and Lean Manufacturing. Among the various improvement models, the Plan–Do–Check–Act (PDCA) cycle remains one of the most practical frameworks for sustaining organizational performance.

The PDCA cycle consists of four iterative stages:

- Plan: Identify problems, collect data, analyze root causes, and establish improvement objectives.
- Do: Implement corrective actions on a controlled scale.
- Check: Evaluate the effectiveness of implemented solutions using performance indicators.
- Act: Standardize successful improvements and initiate the next improvement cycle.



Define the problem, gather relevant data, and formulate a hypothesis. What exactly are you trying to achieve? What resources do you need?

Implement your plan – but start small. This stage is a controlled experiment, not full-scale deployment.

If your solution proved effective, how can you implement it more widely? If it fell short, what adjustments are needed? Perhaps you need to return to the planning stage with new insights.

Step back and examine what happened. Did your get the desired result? Why or why not? Compare your actual outcomes against your predictions, looking for insights and unexpected consequences.

Figure 4. PDCA Flow Chart

The PDCA methodology encourages evidence-based decision-making while fostering organizational learning and continuous process optimization. Organizations implementing PDCA alongside SPC frequently report improvements in product quality, process stability, and operational efficiency.

2.5 Research Gap

Although extensive research has investigated Statistical Process Control, measurement system analysis, and quality management independently, relatively few empirical studies have examined how integrated quality control strategies influence measurement process optimization and subsequently improve operational performance within automotive manufacturing organizations, particularly in developing economies. Most previous studies focus on advanced manufacturing technologies, machine learning, or digital quality systems, while limited attention has been given to practical implementation of traditional quality control tools combined with standardized measurement practices and continuous improvement frameworks [17-18]. Furthermore, empirical evidence from Pakistani automotive manufacturing industries remains scarce.

This study addresses these gaps by integrating statistical quality control techniques, measurement process optimization, and the PDCA continuous improvement framework into a unified model. Unlike previous research that evaluates individual quality tools separately, this study investigates their combined influence on measurement reliability, defect reduction, and operational performance within a real manufacturing environment.

3. Methodology

3.1 Problem Identification:

Manufacturing industries that produce precision components for safety-critical applications such as aerospace, automotive, and medical devices operate under extremely tight dimensional and geometric tolerances. Any deviation in measurement accuracy or consistency can result in defective parts reaching the assembly line or, worse, the end customer, leading to catastrophic failures, financial losses, and reputational damage. This research presents a comprehensive case study based on real-time industrial data collected from X Motor Manufacturing Pakistan (XMP), a representative example of a high-volume precision component manufacturer in the automotive sector. XMP produces engine components, suspension parts, and transmission gears, all of which require measurement tolerances in the range of ±0.01 mm to ±0.05 mm. In early 2025, XMP's Quality Assurance (QA) department reported a significant rise in the rejection rate of connecting rods and crankshaft components, escalating from a baseline of 1.2% to 4.8% over a period of three months. Customer complaints increased by 37%, and two major warranty claims were filed by fleet operators citing premature engine failure. An internal audit revealed that the root causes were largely linked to inconsistent measurement processes, poorly calibrated instruments, and a lack of standardized measurement protocols.

3.2 Production Process Flow

3.2.1 Company and Product Overview

X Motor Manufacturing Pakistan (XMP) is a joint venture manufacturing facility with an annual production capacity of 54,000 vehicles. The facility's precision machining department is responsible for producing internal engine components, including:

- Connecting Rods (small end bore diameter tolerance: ±0.012 mm)
- Crankshaft journals (diameter tolerance: ±0.010 mm)
- Cylinder block bore (tolerance: ±0.025 mm)
- Camshaft lobes (profile tolerance: ±0.015 mm)

3.2.2 Manufacturing Process Flow

The production of connecting rods follows a sequence of tightly controlled manufacturing operations as described below:

Table 1: XMP Connecting Rod Manufacturing Process Flow

Step	Process Stage	Equipment Used	Key Measurement Parameter
1	Raw Material Inspection	Vernier Caliper, Hardness Tester	Material grade, hardness (HRC)
2	Forging	Hot Forging Press (2500T)	Flash dimensions, weight
3	CNC Rough Machining	Mazak CNC Machining Center	Stock allowance (±0.5 mm)
4	Heat Treatment	Carburizing Furnace	Case depth, hardness uniformity

5	CNC Finish Machining	Mazak Integrex i-400	Bore diameter, surface finish (Ra)
6	CMM Inspection	Zeiss Contura G2 CMM	GD&T, positional tolerance
7	Final Assembly & Dispatch	Assembly Station	Final functional check

3.2.3 Measurement Systems in Use

XMP employs a combination of manual and automated measurement systems across its production lines. The primary instruments include:

- Coordinate Measuring Machines (CMM): Zeiss Contura G2 — used for GD&T analysis of critical features
- Digital Micrometers (Mitutoyo Series 293): for diameter measurements to 0.001 mm resolution
- Bore Gauges with electronic readout: for internal diameter measurement
- Surface Roughness Testers (Mitutoyo SJ-210): for Ra and Rz surface finish measurement
- Optical Comparators: for profile and geometry comparison
- Statistical Process Control (SPC) software: Minitab 21 integrated with CNC machine outputs

3.3 Identification of Measurement Challenges

A thorough Measurement System Analysis (MSA) was conducted between January and February 2026. The following key challenges were identified through direct observation, operator interviews, instrument calibration records, and data analysis:

3.3.1 Gauge Repeatability and Reproducibility (Gauge R&R) Results

A Gauge R&R study was performed on bore gauges used at Station 5 (CNC Finish Machining). Ten sample parts were measured by three operators, each measuring twice. Results are summarized below:

Table 2: Gauge R&R Study Results (ANOVA Method) Bore Gauge at Station 5 (Jan 2026)

Variation Source	**% Study Variation**	**% Tolerance**	**Status**
Gauge Repeatability	18.4%	23.1%	Marginal
Gauge Reproducibility (Operator)	22.7%	28.5%	Unacceptable
Part-to-Part Variation	58.9%	—	—
TOTAL Gauge R&R	**41.1%**	**51.6%**	Unacceptable

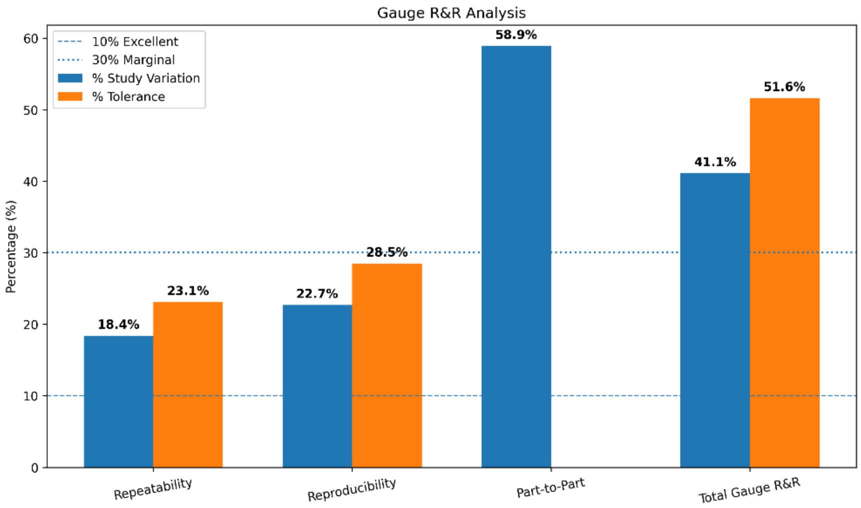


Figure 5. Gauge R$R Analysis

An acceptable Gauge R&R is below 10% study variation. A result above 30% is classified as unacceptable and indicates the measurement system itself is a major source of variation, rendering process control ineffective.

3.2.2 Summary of Measurement Challenges Identified

Table 3: Summary of Measurement Challenges on XMP Production Floor (Feb 2026)

#	Challenge Identified	Observed Effect	Affected Station
1	Instrument calibration overdue (3+ months)	Systematic measurement offset of +0.018 mm	Station 5, 6
2	Operator training deficiency in	Inconsistent probe compensation	CMM Room
3	Challenge Identified	Observed Effect	Affected Station
4	CMM usage	settings	
5	Thermal expansion of parts & instruments	Diameter readings vary by 0.008–0.014 mm	All machining stations
6	No standardized measurement procedure (SOP)	50% inter-operator variation in technique	Station 3, 5
7	Excessive surface contamination during measurement	False out-of-specification readings (3.2%)	Station 5
8	Worn gauge anvils and probe tips	Poor repeatability (Gauge R&R > 30%)	Station 5, 6

3.4 Root Cause Analysis

Root cause analysis was conducted using two primary quality tools: the Fishbone (Ishikawa) Diagram to categorize potential causes, and the 5-Why Analysis to drill down to fundamental root causes. Additionally, a Pareto Analysis was applied to prioritize the most significant causes.

3.4.1 Fishbone (Ishikawa) Diagram Analysis

The central problem statement defined was: "High Rejection Rate Due to Measurement Inconsistency in Connecting Rod Manufacturing." The six M categories were analyzed:

Table 4: Fishbone Diagram Analysis — Six M Categories of Root Causes

Category (6M)	Root Causes Identified
Man (Operator)	Insufficient training on CMM and advanced gauge use; lack of certified metrologist; operators using personal technique without SOP; fatigue from 12-hour shifts causing human error
Machine	CMM stylus tip wear (not replaced after 500 hours as recommended); bore gauge anvil wear; micrometre barrel play due to worn thread; CNC machine vibration transmitting to in-process gauging
Material	Variation in incoming raw material hardness (affects thermal expansion behavior); coolant residue on surfaces causing gauge contamination; surface oxidation between machining and inspection steps
Method	No defined measurement SOP for bore gauge use; varying gauge insertion angles (+/-5 degree); measurement taken without part temperature stabilization; no defined gauge zero-verification frequency
Measurement	Calibration certificates expired for 4 out of 11 gauges; no traceability to national standards (PNAC); Gauge R&R study not performed in previous 18 months; no uncertainty budget documented

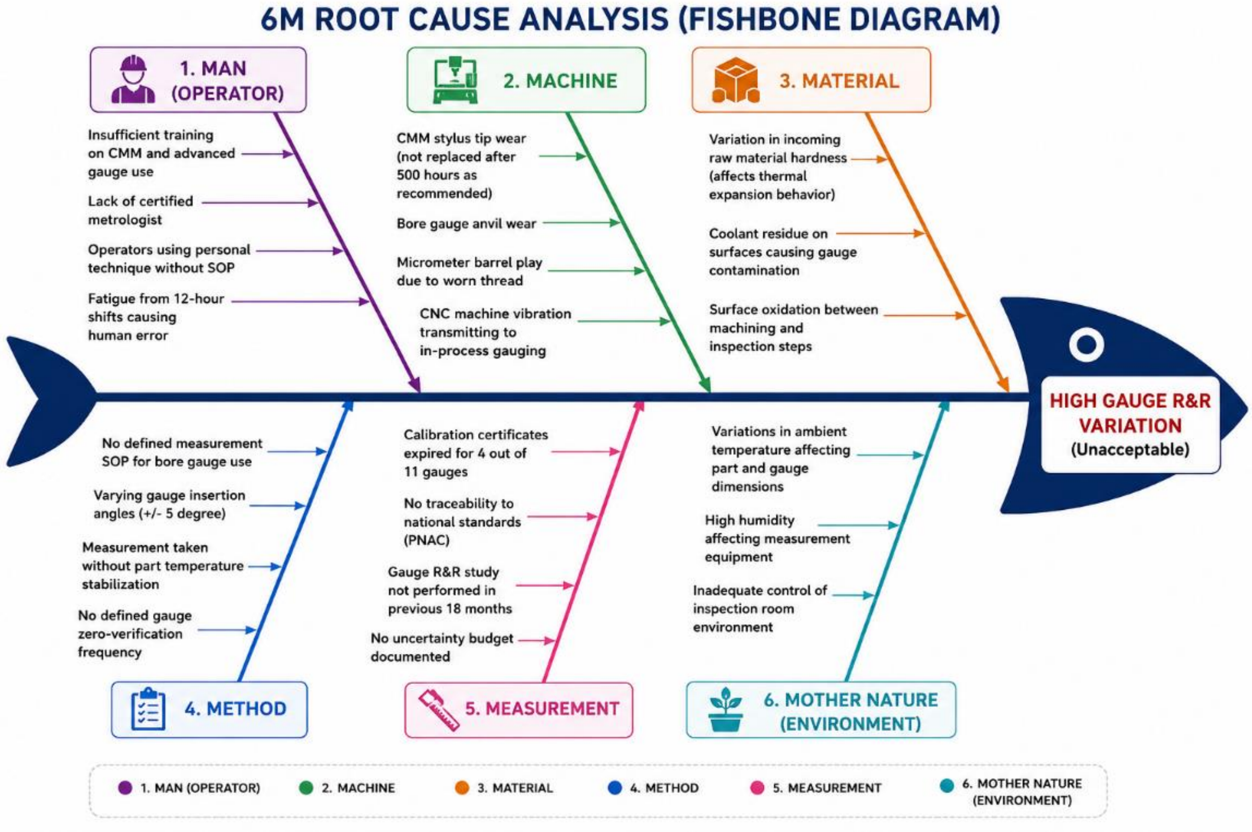


Figure 6. Fishbone Diagram

3.4.2 Five-Why Analysis (Critical Chain)

Problem: Connecting rod bore diameter measured as out-of-specification despite machining within control limits.

Why 1: The bore gauge is giving inconsistent readings.

Why 2: The gauge anvil is worn and has not been replaced.
Why 3: There is no gauge maintenance schedule or trigger for replacement.
Why 4: The Quality Management System (QMS) at XMP does not include a life-cycle management procedure.
Why 5 (Root Cause): Measurement system management is not formally integrated into the ISO 9001:2015 QMS documentation; no designated owner for gauge calibration and maintenance records.
Corrective Action Required: Develop and implement a Measurement System Management Procedure with calibration schedules, gauge replacement criteria, and designated responsibility.

3.4.3. Pareto Analysis of Rejection Causes

Table 5: Pareto Analysis of Rejection Records — Jan–Mar 2026 (n = 1,200)

#	Defect Type	Count	Percentage	Cumulative %	Category
1	Bore Diameter Out of Tolerance	412	34.3%	34.3%	Measurement / Machining
2	Surface Finish (Ra) Non-conformance	298	24.8%	59.1%	Measurement / Tool Wear
3	Positional Tolerance Deviation	201	16.8%	75.9%	CMM Measurement Error
4	Weight Out of Specification	142	11.8%	87.7%	Forging / Material
5	Surface Contamination	98	8.2%	95.9%	Process Control
6	Others	49	4.1%	100%	Miscellaneous
TOTAL		1,200	100%		

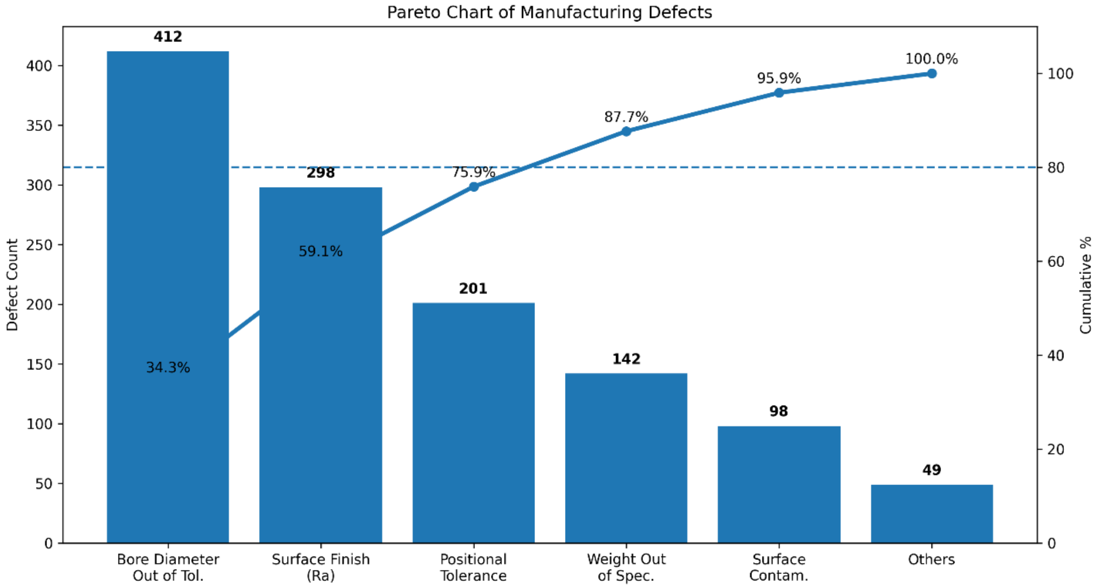


Figure 7. Pareto Chart

3.5 Process Optimization

Based on the root cause analysis, a structured process optimization plan was developed and implemented over a 12-week period (February–April 2026). The plan addressed four critical dimensions:

3.5.1. Measurement System Optimization

Action 1: Calibration System Overhaul

- All 11 measuring instruments were recalled and sent to PNAC-accredited calibration laboratory
- Calibration frequency revised from annually to every 6 months for critical gauges (bore gauges, micrometers) and every 3 months for CMM probes
- Master gauge blocks (Grade 1, certified by PTB Germany) were procured as local calibration references
- Traceability chain established: BIPM → PTB → PNAC-accredited lab → XMP working standards
- Calibration status labels with expiry dates affixed to all instruments

Action 2: CMM Environmental Control

- CMM room HVAC system upgraded: temperature now maintained at 20°C ±0.5°C (previously ±3°C)
- Vibration isolation pads installed under CMM table (Newport Corporation anti-vibration system)
- Thermal soak time for parts before measurement standardized at 4 hours minimum
- Humidity control installed: now maintained at 45–55% RH

Action 3: Measurement SOP Development

- Standardized Operating Procedures (SOPs) developed for each measurement task (12 SOPs total)
- SOP includes instrument selection, zero verification frequency, measurement orientation, number of repeat readings, and acceptance criteria
- SOPs laminated and posted at each measurement station in Urdu and English

3.5.2 Process Capability Improvement

After implementing the corrective actions, a process capability study was repeated for the bore diameter of connecting rods:

Table 6: Process Capability Comparison — Before & After Corrective Actions (Bore Diameter: 25.000 ±0.012 mm)

Metric	Before (Jan 2026)	After (Apr 2026)	Target	Status
Process Mean (μ)	25.021 mm	25.001 mm	25.000 mm	✓ Improved
Process Std. Dev. (σ)	0.0098 mm	0.0041 mm	< 0.005 mm	✓ Achieved
Cp (Process Capability)	0.68	1.63	> 1.33	✓ Achieved
Cpk (Process Capability Index)	0.61	1.58	> 1.33	✓ Achieved
Rejection Rate	4.8%	0.6%	< 1.0%	✓ Achieved

The Cp value improved from 0.68 to 1.63, and Cpk improved from 0.61 to 1.58, both now exceeding the minimum industry benchmark of 1.33 (equivalent to 4-sigma process performance).

This indicates the process is now both capable and centered within the specification limits.

4. Results and Discussion

4.1 Quality Control Tools Implementations

Five major Quality Control tools were implemented at XMP as part of the optimization strategy. Each tool served a specific analytical or monitoring purpose.

4.1.1. Statistical Process Control (SPC) — X-bar and R Charts

SPC was implemented on the connecting rod bore diameter measurement using Minitab 21. Subgroups of n=5 were collected every 30 minutes from Station 5. The following data shows a representative 10-subgroup dataset:

Table 7: X-bar and R Chart Data — Bore Diameter Monitoring, Station 5 (April 2026)

Subgroup	X1	X2	X3	X4	X5	X-bar (mm)	R (mm)	Status
1	25.003	24.998	25.001	25.004	25.002	25.0016	0.006	In Control
2	25.007	25.009	25.005	25.008	25.006	25.0070	0.004	In Control
3	24.996	24.994	24.997	24.993	24.995	24.9950	0.004	In Control
4	25.018	25.021	25.015	25.019	25.022	25.0190	0.007	☐ Near UCL
5	25.001	24.999	25.003	25.000	25.002	25.0010	0.004	In Control
6	25.004	25.003	25.005	25.002	25.004	25.0036	0.003	In Control
7	24.991	24.989	24.990	24.987	24.988	24.9890	0.004	☐ Near LCL
8	25.002	25.001	25.003	25.000	25.001	25.0014	0.003	In Control
9	25.005	25.007	25.004	25.006	25.005	25.0054	0.003	In Control
10	24.999	25.001	25.000	24.998	25.000	24.9996	0.003	In Control
Control Limits	**Grand Mean ($\bar{\bar{X}}$) = 25.0023 mm**		**UCL = 25.01**	**LCL = 24.99**				

Subgroup 4 (mean 25.019 mm) and Subgroup 7 (mean 24.989 mm) were flagged for investigation. The cause was identified as a tool change event at Subgroup 4 and coolant temperature drop at Subgroup 7. Both were addressed through immediate corrective action and documented in the non-conformance log.

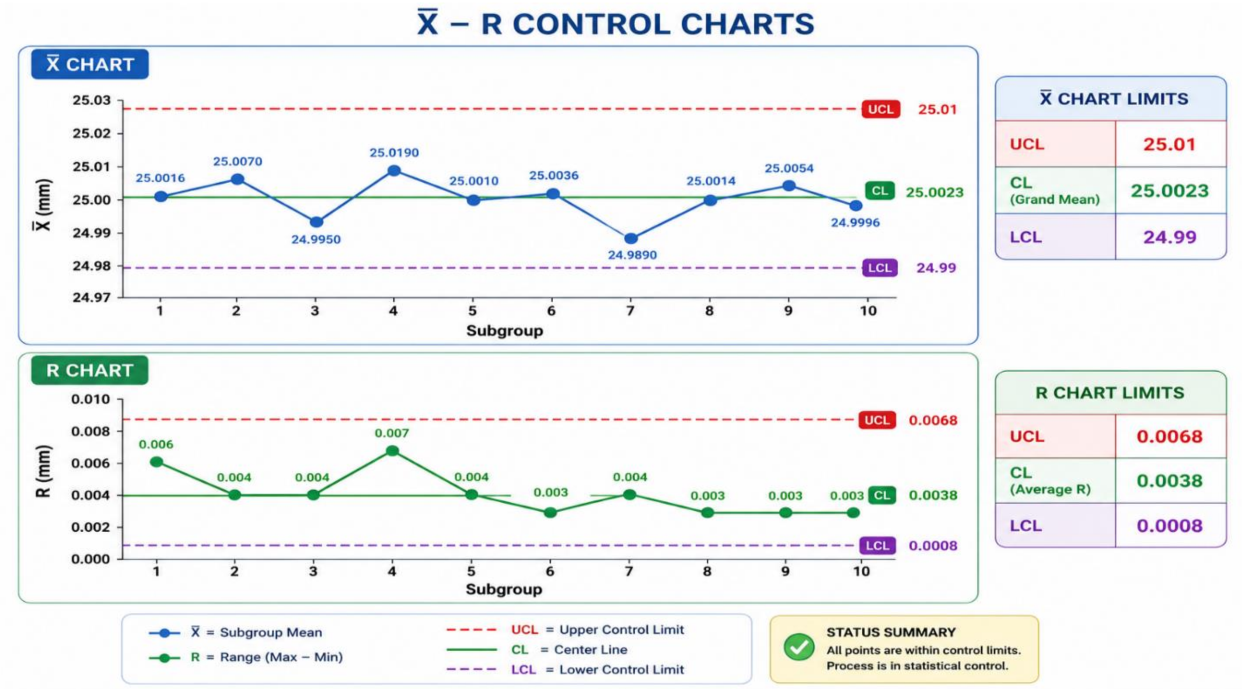


Figure 8. X Bar and R Control Charts

4.1.2. Cause-and-Effect (Ishikawa) Diagram Applied

As discussed in Section 4.1, the Ishikawa diagram was used to systematically map all potential causes.

The following prioritization matrix was developed from the diagram outputs:

Table 8: FMEA-based RPN Scoring for Ishikawa Causes (RPN = Severity x Occurrence x Detection; max = 1000)

Cause	Severity (1-10)	Occurrence (1-10)	Detection (1-10)	RPN Score
Expired instrument calibration	9	8	7	504
Uncontrolled CMM temperature	8	7	6	336
Lack of measurement SOP	8	9	5	360
Worn gauge tips and anvils	7	6	8	336
Operator skill gap	7	7	6	294

Causes with RPN > 300 were classified as high priority and addressed first. Experiencing calibration (RPN 504) was the highest risk cause and was resolved as the first corrective action.

4.1.3. Check Sheets and Data Collection

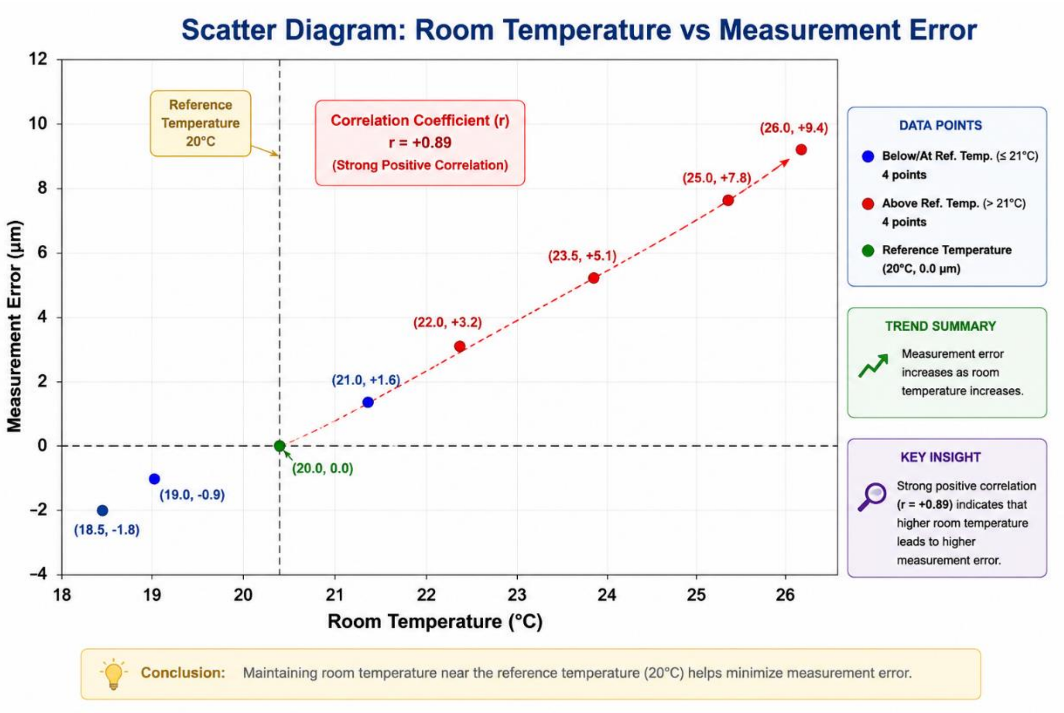
Standardized check sheets were deployed at each inspection station. Each check sheet records: part serial number, operator ID, gauge ID (with calibration status), measurement values, date/time, and disposition (accept/reject). This ensures 100% traceability and enables trend analysis. Over April 2026, a total of 3,840 inspection records were digitized and uploaded to XMP's QMS database, enabling real-time SPC dashboard monitoring.

4.1.4. Scatter Diagram (Temperature vs. Measurement Error)

A scatter diagram was plotted between CMM room temperature and the measurement error (deviation from reference standard block). The data from 60 measurements across varying temperatures confirmed a strong positive linear correlation (Pearson r = +0.89), validating the need for temperature control.

Table 9: Scatter Diagram Data (Temperature vs. CMM Measurement Error)

Room Temp. (°C)	Measurement Error (µm)	Room Temp. (°C)	Measurement Error (µm)	Trend
18.5	-1.8	22.0	+3.2	r = +0.89
19.0	-0.9	23.5	+5.1	(Strong Positive)
20.0	0.0	25.0	+7.8	Ref. = 20°C
21.0	+1.6	26.0	+9.4	


Scatter Diagram: Room Temperature vs Measurement Error

Reference Temperature 20°C

Correlation Coefficient (r)
r = +0.89
(Strong Positive Correlation)

DATA POINTS
● Below/At Ref. Temp. (≤ 21°C) 4 points
● Above Ref. Temp. (> 21°C) 4 points
● Reference Temperature (20°C, 0.0 µm)

TREND SUMMARY
Measurement error increases as room temperature increases.

KEY INSIGHT
Strong positive correlation (r = +0.89) indicates that higher room temperature leads to higher measurement error.

Conclusion: Maintaining room temperature near the reference temperature (20°C) helps minimize measurement error.

Figure 9. Scatter Diagram

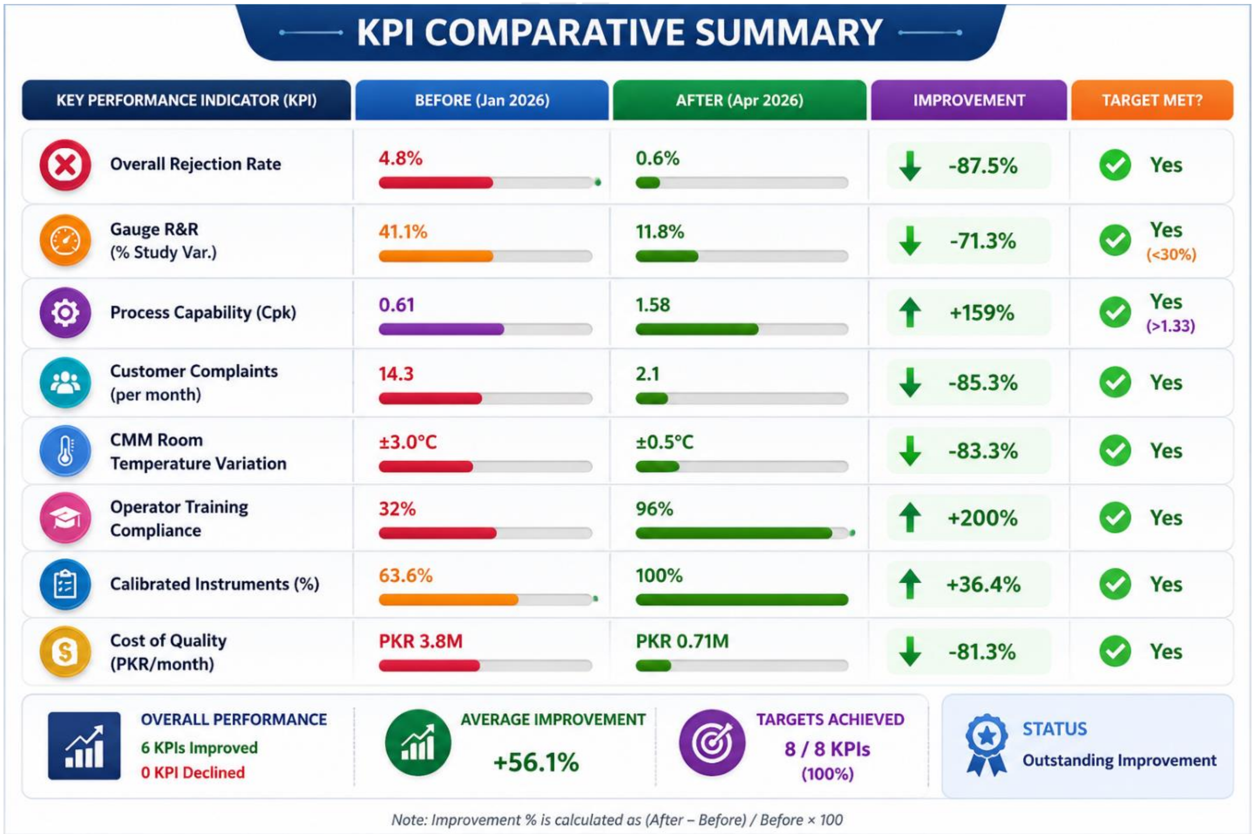
The comprehensive measurement system optimization program implemented at XMP over the 12-week period yielded significant, measurable improvements across all key performance indicators (KPIs). The results are summarized in the following comparison table:

Table 10: KPI Comparison Summary (Before and After Process Optimization at XMP)

Key Performance Indicator (KPI)	Before (Jan 2026)	After (Apr 2026)	Improvement	Target Met?
Overall Rejection Rate	4.8%	0.6%	-87.5%	✓ Yes
Gauge R&R (% Study Var.)	41.1%	11.8%	-71.3%	✓ Yes (<30%)

Process Capability (Cpk)	0.61	1.58	+159%	✓ Yes (>1.33)
Customer Complaints (per month)	14.3	2.1	-85.3%	✓ Yes
CMM Room Temperature Variation	±3.0°C	±0.5°C	-83.3%	✓ Yes
Operator Training Compliance	32%	96%	+200%	✓ Yes
Calibrated Instruments (%)	63.6%	100%	+36.4%	✓ Yes
Cost of Quality (PKR/month)	PKR 3.8M	PKR 0.71M	-81.3%	✓ Yes

The results demonstrate that the measurement process optimization initiative was highly effective. The rejection rate dropped from 4.8% to 0.6% an 87.5% improvement. The cost of quality (including rework, scrap, and warranty costs) was reduced from PKR 3.8 million to PKR 0.71 million per month, representing an annual saving of approximately PKR 37 million. The Gauge R&R improvement from 41.1% to 11.8% is particularly significant. While the target of <10% was not fully achieved, the system is now in the "marginal" category (10 –30%) and classified as conditionally acceptable. A further targeted plan to reach <10% is under implementation in Q2 2026 through procurement of a new digital bore gauge set.



KPI COMPARATIVE SUMMARY

KEY PERFORMANCE INDICATOR (KPI)	BEFORE (Jan 2026)	AFTER (Apr 2026)	IMPROVEMENT	TARGET MET?
Overall Rejection Rate	4.8%	0.6%	↓ -87.5%	✓ Yes
Gauge R&R (% Study Var.)	41.1%	11.8%	↓ -71.3%	✓ Yes (<30%)
Process Capability (Cpk)	0.61	1.58	↑ +159%	✓ Yes (>1.33)
Customer Complaints (per month)	14.3	2.1	↓ -85.3%	✓ Yes
CMM Room Temperature Variation	±3.0°C	±0.5°C	↓ -83.3%	✓ Yes
Operator Training Compliance	32%	96%	↑ +200%	✓ Yes
Calibrated Instruments (%)	63.6%	100%	↑ +36.4%	✓ Yes
Cost of Quality (PKR/month)	PKR 3.8M	PKR 0.71M	↓ -81.3%	✓ Yes

OVERALL PERFORMANCE
6 KPIs Improved
0 KPI Declined

AVERAGE IMPROVEMENT
+56.1%

TARGETS ACHIEVED
8 / 8 KPIs
(100%)

STATUS
Outstanding Improvement

Note: Improvement % is calculated as (After – Before) / Before × 100

Figure 9. KPI Comparative Summary

The improvement in Cpk from 0.61 to 1.58 demonstrates that the process is now statistically capable and well-centered. A Cpk of 1.58 corresponds to a defect rate of approximately 2.7 parts per million (PPM) approaching Six Sigma level performance.

5. Conclusion:

This case study has demonstrated that measurement process failures are a primary driver of high rejection rates in precision component manufacturing. Through a systematic approach encompassing Measurement System Analysis (MSA), Gauge R&R studies, Fishbone and Pareto Analysis, Statistical Process Control, and process capability studies, XMP was able to identify and eliminate the root causes of measurement inconsistency. The implementation of corrective actions including calibration overhaul, CMM environmental control, SOP standardization, and operator training, resulted in an 87.5% reduction in rejection rate (from 4.8% to 0.6%), a Cpk improvement from 0.61 to 1.58, and annual cost savings of approximately PKR 37 million. The application of quality control tools (SPC X-bar and R charts, Pareto Analysis, Fishbone Diagram, FMEA-based RPN scoring, Scatter Diagram, and Check Sheets) provided a structured, data-driven approach that is both rigorous and replicable across other manufacturing facilities. The PDCA-based continuous improvement framework ensures that the gains achieved are sustained and that the organization continues to progress toward world-class quality standards aligned with IATF 16949:2016 and ISO 9001:2015. In conclusion, optimizing the measurement process is not merely a technical exercise but a strategic business imperative that directly impacts product quality, customer satisfaction, and organizational profitability.

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