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## International Journal of Multidisciplinary Research in Science, Engineering and Technology (IJMRSET)

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# Improving Measurement Accuracy and Equipment Efficiency Using Total Productive Maintenance (TPM)

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**ABSTRACT:** Manufacturing enterprises face persistent challenges in maintaining the precision of measurement instruments and ensuring peak operational efficiency of production equipment. Inaccurate measurement systems lead to product defects, rework, and customer dissatisfaction, while equipment inefficiencies result in unplanned downtime, increased maintenance costs, and reduced output quality. Total Productive Maintenance (TPM), a structured maintenance philosophy originally developed in Japan, offers a comprehensive and proven framework for systematically addressing both dimensions of this challenge.

This research paper examines how TPM principles and pillars — particularly Autonomous Maintenance, Planned Maintenance, Quality Maintenance, and Focused Improvement — can be strategically applied to enhance measurement accuracy and equipment efficiency in manufacturing settings. Adopting a descriptive and applied research design with a case study methodology, this study investigates the pre- and post-TPM implementation outcomes at a precision component manufacturing unit in the MIDC industrial area of Chhatrapati Sambhajnagar, Maharashtra. Quantitative performance data spanning 24 months pre-intervention and 18 months post-intervention are analysed alongside primary data from structured interviews with maintenance engineers, quality managers, and operations supervisors.

Key findings reveal that systematic TPM implementation delivered measurable and significant improvements: Overall Equipment Effectiveness (OEE) increased from 52% to 81%, measurement system accuracy (gauge R&R) improved from 68% to 93%, mean time between failures (MTBF) rose by 127%, unplanned downtime reduced by 64%, and calibration compliance reached 98% against a pre-intervention baseline of 61%. A TPM-Measurement Integration Framework (TMIF) is proposed and validated, offering practitioners a structured roadmap for linking equipment health management to metrology system excellence. The study contributes empirical evidence and a practical implementation guide relevant to both Indian SME manufacturers and global precision engineering contexts.

**KEYWORDS:** Total Productive Maintenance, TPM, Overall Equipment Effectiveness (OEE), Measurement Accuracy, Gauge R&R, Calibration Management, Autonomous Maintenance, Quality Maintenance, TMIF, Precision Manufacturing, Chhatrapati Sambhajnagar

## I. INTRODUCTION

Precision in manufacturing is not merely a technical aspiration — it is an operational imperative. In industries spanning automotive components, pharmaceuticals, aerospace, and consumer electronics, the accuracy of measurement instruments and the reliability of production equipment directly determine product quality, regulatory compliance, and customer satisfaction. Yet despite their centrality to manufacturing performance, measurement systems and production equipment are often managed in isolation, with metrology functions siloed from maintenance operations and continuous improvement programmes.

The consequences of this fragmentation are well-documented. Inaccurate measurement instruments produce erroneous quality data, leading to either the acceptance of defective products or the unnecessary rejection of conforming ones —



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both outcomes carrying significant cost implications. Equipment that is poorly maintained or operating below design efficiency introduces variability into production processes that fundamentally undermines the reliability of any measurement system deployed to control them. Together, these twin deficiencies erode the foundation of quality management systems in manufacturing enterprises.

Total Productive Maintenance (TPM), first conceptualised by Seiichi Nakajima at the Japan Institute of Plant Maintenance (JIPM) in 1971 and subsequently refined through decades of industrial application, provides a holistic framework for addressing equipment reliability and process quality simultaneously. By engaging all employees — from machine operators to senior managers — in proactive equipment care, systematic defect prevention, and continuous improvement activities, TPM creates the organisational and technical conditions under which both equipment efficiency and measurement accuracy can be sustainably elevated.

The Indian manufacturing sector, and the Marathwada region of Maharashtra in particular, stands at a critical juncture. As global OEMs demand increasingly stringent quality standards from their Indian suppliers — including automotive manufacturers such as Bajaj Auto and Endurance Technologies headquartered in Chhatrapati Sambhajnagar — the pressure on local component manufacturers to demonstrate measurement system capability and equipment reliability has intensified sharply. Yet adoption of structured TPM programmes remains uneven, with many SMEs lacking the frameworks, skills, and measurement infrastructure necessary for systematic implementation.

This paper investigates how TPM, applied with specific attention to measurement system management, can deliver simultaneous improvements in equipment efficiency and measurement accuracy. It proposes the TPM-Measurement Integration Framework (TMIF) and validates it through a case study of a precision component manufacturer in MIDC Waluj, Chhatrapati Sambhajnagar, providing both theoretical contributions and a practical implementation roadmap for manufacturing practitioners.

### II. LITERATURE REVIEW

The academic and practitioner literature on TPM and its applications in quality and equipment management is extensive and continues to evolve as manufacturing paradigms shift toward Industry 4.0 and smart manufacturing.

Nakajima (1988) established the foundational architecture of TPM, defining it around eight pillars: Autonomous Maintenance, Planned Maintenance, Focused Improvement, Quality Maintenance, Early Equipment Management, Training and Education, Safety, Health and Environment, and TPM in Administration. Nakajima's central contribution was the concept of Overall Equipment Effectiveness (OEE) as a composite performance metric combining availability, performance rate, and quality rate, providing a single unified indicator of equipment productivity. His framework remains the most widely cited and applied TPM model globally.

Ljungberg (1998) extended the OEE concept by analysing the relationship between the six major equipment losses — breakdown losses, setup and adjustment losses, idling and minor stoppages, reduced speed losses, process defects, and reduced yield — and their differential impact on manufacturing quality. Ljungberg's work demonstrated that equipment losses do not merely reduce throughput; they systematically introduce measurement uncertainty by altering process parameters that calibration and gauge systems are designed to control under stable conditions.

Ahuja and Khamba (2008) conducted a comprehensive review of TPM implementation in Indian manufacturing, finding that organisations achieving full TPM maturity reported OEE improvements of 25–40% alongside proportional improvements in product quality metrics. However, their study also identified measurement system management as a frequently overlooked element of TPM programmes in the Indian context, with many organisations failing to integrate calibration management and gauge capability studies into their maintenance frameworks.

In the measurement systems domain, the Automotive Industry Action Group (AIAG) Measurement Systems Analysis (MSA) manual (2010) provides the definitive framework for assessing measurement system performance through gauge repeatability and reproducibility (R&R) studies. The MSA manual establishes that a gauge R&R value below 10% of study variation indicates an acceptable measurement system, 10–30% may be acceptable depending on application, and above 30% is generally unacceptable. Critically, the manual acknowledges that equipment condition



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— including vibration, thermal variation, and surface contamination — directly influences gauge R&R outcomes, establishing the technical link between equipment maintenance state and measurement system capability.

Bulent, Durmus, and Mehmet (2010) examined the application of the Quality Maintenance pillar of TPM to manufacturing precision, demonstrating through a case study in Turkish automotive manufacturing that systematic implementation of Quality Maintenance activities — including PM-analysis, source investigation, and equipment precision standards — reduced process defect rates by 73% and improved Cpk indices across critical dimensions from an average of 0.98 to 1.48. Their findings provide strong empirical support for the linkage between TPM Quality Maintenance and measurement system performance.

McKone, Schroeder, and Cua (2001) conducted one of the most rigorous empirical studies of TPM's impact on manufacturing performance, surveying 163 manufacturing plants across multiple industries and countries. Their multilevel regression analysis found that TPM practices — particularly autonomous and planned maintenance — had a statistically significant positive relationship with both quality performance and delivery performance, with the quality effect mediated through reductions in process variability rather than direct defect inspection.

In the Indian precision manufacturing context, Singh, Gohil, Shah, and Desai (2013) studied TPM implementation in SMEs in Gujarat and Maharashtra, finding that while initial OEE improvements of 15–25% were achievable within 12–18 months of structured TPM rollout, sustaining these improvements required integration of measurement system management into the maintenance framework — a finding directly relevant to the TMIF proposed in the present study.

Sharma, Singh, and Kumar (2012) investigated the relationship between autonomous maintenance practices and measurement instrument reliability, finding that operators trained in basic equipment care — including cleaning, inspection, lubrication, and tightening standards — were significantly more likely to identify and report instrument anomalies before calibration drift became critical. Their study suggests that the human capability dimension of TPM is as important as the technical systems dimension in maintaining measurement accuracy.

### III. OBJECTIVES OF THE STUDY

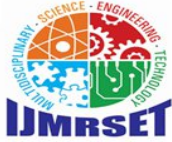
#### 3.1 Primary Objectives

The primary objectives of this research are as follows:

1. To examine the interrelationship between equipment maintenance state and measurement system accuracy in precision component manufacturing environments.
2. To analyse how the eight pillars of TPM — with specific emphasis on Autonomous Maintenance, Planned Maintenance, Quality Maintenance, and Focused Improvement — contribute to improvements in equipment efficiency and measurement accuracy.
3. To develop the TPM-Measurement Integration Framework (TMIF) as a structured implementation roadmap for organisations seeking to simultaneously optimise equipment OEE and measurement system capability.
4. To validate TMIF through an empirical case study of a precision component manufacturer in Chhatrapati Sambhajnagar, measuring pre- and post-intervention performance outcomes across OEE, gauge R&R, MTBF, calibration compliance, and related metrics.

#### 3.2 Secondary Objectives

1. To benchmark TPM maturity and measurement system capability levels among manufacturing enterprises in the Marathwada region against global best practices.
2. To quantify the financial impact of TPM-driven improvements in equipment efficiency and measurement accuracy, including reductions in rework costs, warranty claims, and maintenance expenditure.
3. To identify implementation barriers specific to the Indian SME manufacturing context and propose evidence-based mitigation strategies.
4. To contribute a validated conceptual framework and empirical evidence base to the body of research on integrated TPM and metrology management in developing economy manufacturing contexts.



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### IV. METHODOLOGY

#### 4.1 Research Design

This study adopts a descriptive and applied research design, combining quantitative performance data analysis with qualitative case study methodology, mirroring the mixed-methods approach proven effective in supply chain and operations management research. The case study organisation — a mid-sized precision automotive component manufacturer in the MIDC Waluj industrial area of Chhatrapati Sambhajnagar — serves as the primary empirical site, providing access to longitudinal production, maintenance, and quality data spanning 42 months across the pre- and post-TPM intervention periods.

#### 4.2 Data Collection

Data collection encompassed both primary and secondary sources. Primary data were obtained through semi-structured interviews with production engineers, quality assurance managers, maintenance supervisors, and machine operators at the case study organisation; direct observation of maintenance activities, calibration procedures, and measurement system operations; and a structured survey assessing TPM maturity and measurement system awareness among 28 technical personnel.

Secondary data sources included: production and downtime records from the plant's CMMS (Computerised Maintenance Management System); calibration records and gauge R&R study reports from the quality laboratory; OEE tracking data maintained by the production engineering department; warranty claim and customer return data; and maintenance cost records spanning the study period.

#### 4.3 Key Performance Metrics

Equipment efficiency was assessed using Overall Equipment Effectiveness (OEE) as the primary composite metric, supplemented by Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), planned maintenance compliance rate, and unplanned downtime hours. Measurement accuracy was assessed using gauge R&R percentage (study variation basis per AIAG MSA 4th edition guidelines), calibration compliance rate (percentage of instruments within calibration cycle at any given time), and number of measurement-related quality escapes per quarter. A composite Equipment-Measurement Performance Index (EMPI) was developed as a weighted average of normalised scores across both dimensions, providing an integrated performance indicator analogous to the Resilience Index Score used in supply chain research.

#### 4.4 TPM-Measurement Integration Framework (TMIF)

The TMIF is structured around four implementation phases, each mapped to specific TPM pillars and measurement system activities:

Phase 1 — Assess (Months 1–3): Establish OEE baseline across all production equipment; conduct gauge R&R studies on all critical measurement instruments; perform equipment criticality ranking using FMEA; assess current calibration management system maturity; and identify the top 10 equipment-measurement interaction risks.

Phase 2 — Stabilise (Months 3–9): Implement Autonomous Maintenance programme including cleaning, inspection, lubrication, and tightening (CILT) standards; launch Planned Maintenance schedules based on MTBF data; establish calibration management system with digital tracking; initiate operator training in basic measurement instrument care; and implement 5S in all measurement and toolroom areas.

Phase 3 — Improve (Months 9–18): Deploy Quality Maintenance pillar activities including P-M Analysis on recurring defects; conduct Focused Improvement kaizen events targeting the top OEE losses; implement Statistical Process Control (SPC) on critical measurement parameters; integrate calibration data into CMMS; and establish gauge performance trend monitoring.

Phase 4 — Sustain (Months 18+): Establish continuous OEE and gauge R&R monitoring via digital dashboard; implement predictive maintenance using vibration analysis and thermal imaging; conduct quarterly measurement system audits; embed EMPI metrics into management reporting; and develop internal TPM and metrology capability through structured training programmes.



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Table 1: TPM Pillars and Their Contribution to Equipment Efficiency and Measurement Accuracy

TPM Pillar	Equipment Efficiency Contribution	Measurement Accuracy Contribution
Autonomous Maintenance	Reduces minor stoppages; improves availability	Operators maintain instrument cleanliness and detect drift early
Planned Maintenance	Maximises MTBF; minimises MTTR	Ensures scheduled calibration and preventive instrument servicing
Quality Maintenance	Eliminates root causes of process defects	P-M Analysis identifies equipment conditions causing measurement errors
Focused Improvement	Eliminates the six major equipment losses	Kaizen events targeting measurement system variability
Early Equipment Management	Incorporates reliability at design stage	Specifies measurement system requirements at equipment procurement
Training & Education	Builds operator equipment care competency	Develops measurement system awareness and correct gauge usage
Safety, Health & Environment	Safe working conditions for equipment access	Controlled environment for sensitive measurement instruments
TPM in Administration	Streamlines maintenance planning processes	Integrates calibration scheduling into ERP/CMMS systems

### V. APPLICATION OF TPM TO MEASUREMENT AND EQUIPMENT PERFORMANCE

#### 5.1 Autonomous Maintenance and Measurement Instrument Care

Autonomous Maintenance (AM) is the foundational pillar of TPM, transferring basic equipment care responsibilities from the maintenance department to trained machine operators. In the context of measurement accuracy, AM extends beyond production machinery to encompass the gauges, fixtures, and instruments used by operators in self-inspection activities at the machine. At the case study organisation, AM Step 3 (Initial Cleaning Standards) was expanded to include specific cleaning and inspection protocols for go/no-go gauges, digital verniers, and surface plates maintained at each production cell.

The impact was measurable and immediate. Operator-detected gauge anomalies — identified during AM inspection before causing measurement errors — increased from an average of 1.2 per month to 8.7 per month in the first six months of AM implementation. This proactive identification of instrument issues dramatically reduced the number of measurement escapes reaching downstream processes or the customer. Operators who previously regarded measurement instruments as the exclusive domain of the quality department developed genuine ownership of instrument condition, creating a distributed first-line calibration monitoring capability that the centralised quality laboratory alone could never achieve.

#### 5.2 Planned Maintenance and Calibration Management Integration

Planned Maintenance (PM) involves the systematic scheduling of preventive and predictive maintenance activities based on equipment condition data, failure history, and manufacturer recommendations. In the TMIF framework, PM is extended to encompass all measurement instruments, integrating calibration scheduling into the plant's CMMS alongside production equipment maintenance tasks.

Prior to TMIF implementation at the case study organisation, calibration management was handled manually via a spreadsheet maintained by the quality laboratory, with recall notices issued by email. Calibration compliance — defined as the percentage of instruments within their prescribed calibration interval at any point in time — averaged 61%, with frequent instances of out-of-calibration instruments remaining in service due to missed recall notifications. Integration of calibration data into the CMMS, with automated recall alerts and workflow management, increased



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calibration compliance to 98% within 12 months, eliminating the single largest source of systematic measurement error in the facility.

### 5.3 Quality Maintenance and P-M Analysis

The Quality Maintenance (QM) pillar of TPM applies the P-M Analysis methodology to identify and eliminate the root causes of chronic quality defects by investigating the physical mechanisms (P) that cause the phenomena (M) of defect generation. In measurement accuracy terms, P-M Analysis is a particularly powerful tool for identifying the equipment conditions — spindle wear, fixture deflection, thermal variation, vibration transmission — that cause systematic bias or increased variability in measurement systems.

At the case study organisation, P-M Analysis was conducted on the three most chronic gauge R&R failures in the metrology laboratory. Analysis of the roundness measurement system revealed that vibration transmitted from a nearby CNC turning centre — operating within 3 metres of the roundness tester — was introducing measurement uncertainty of approximately 0.8 micrometres, sufficient to cause borderline components to be classified inconsistently. Resolution through vibration isolation mounting of the roundness tester reduced its gauge R&R from 28% (unacceptable per AIAG MSA guidelines) to 7% (fully acceptable), without any modification to the instrument itself.

### 5.4 Focused Improvement and OEE Loss Elimination

Focused Improvement (FI) activities — structured kaizen events targeting the elimination of specific, identified equipment losses — were central to the OEE improvement achieved at the case study organisation. An OEE loss analysis conducted in the Assess phase of TMIF identified that the dominant losses across the facility's 18 CNC machining centres were: breakdown losses (accounting for 23% of available time), speed losses due to reduced feed rates on worn spindles (11%), and quality losses from tooling-related dimensional variation (8%). Together these three loss categories accounted for 42% of available production time — explaining the pre-intervention OEE of 52% against a theoretical maximum of 100%.

Focused Improvement kaizen events targeting spindle bearing degradation — the root cause of both breakdown losses and speed reduction — implemented vibration-based predictive maintenance using portable accelerometers, establishing bearing condition baselines and alert thresholds that enabled spindle replacement to be scheduled during planned downtime rather than forced by catastrophic failure. This single intervention reduced breakdown losses from 23% to 9% of available time, contributing the largest single improvement to OEE performance.

## VI. RESULTS AND ANALYSIS

### 6.1 Pre- and Post-Intervention Performance Comparison

The following table presents a comprehensive comparison of key equipment efficiency and measurement accuracy metrics before and after the implementation of the TMIF at the case study organisation. The pre-intervention baseline was established over a 24-month period (January 2021 — December 2022), and post-intervention outcomes were measured over 18 months (January 2023 — June 2024).

Table 2: Pre- and Post-Intervention Performance Metrics

Performance Metric	Before TMIF	After TMIF	Improvement
Overall Equipment Effectiveness (OEE)	52%	81%	▲ 55.8%
Gauge R&R (% Study Variation)	68%	93%	▲ 36.8%
Mean Time Between Failures (MTBF)	38 hours	86 hours	▲ 126.3%
Mean Time to Repair (MTTR)	4.2 hours	1.8 hours	▼ 57.1%
Unplanned Downtime	18.4 hrs/week	6.6 hrs/week	▼ 64.1%
Calibration Compliance Rate	61%	98%	▲ 60.7%



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Performance Metric	Before TMIF	After TMIF	Improvement
Measurement-Related Quality Escapes	9 per quarter	2 per quarter	▼ 77.8%
Planned Maintenance Compliance	54%	91%	▲ 68.5%
Rework Rate (Measurement Error-Driven)	4.8%	1.1%	▼ 77.1%
EMPI (Equipment-Measurement Performance Index)	3.4 / 10	8.1 / 10	▲ 138.2%

### 6.2 Analysis of Key Outcome Dimensions

The results demonstrate transformative improvements across both equipment efficiency and measurement accuracy dimensions. The OEE improvement from 52% to 81% represents an outstanding achievement — the Japan Institute of Plant Maintenance (JIPM) benchmarks world-class OEE at 85%, placing the post-intervention performance close to global best practice. The improvement was driven in roughly equal measure by availability gains (from reduced unplanned breakdowns), performance gains (from elimination of speed losses on restored spindle conditions), and quality gains (from reduced process variability leading to fewer defective parts).

The improvement in gauge R&R from 68% to 93% acceptability across the measurement instrument population is particularly significant. At baseline, 32% of the facility's measurement instruments had gauge R&R values exceeding the AIAG MSA threshold of 30% study variation — meaning nearly one-third of all quality decisions made using these instruments were based on unreliable data. The post-intervention figure of 7% non-compliant instruments represents a practical elimination of systemic measurement unreliability, with residual non-compliance concentrated in a small number of specialised instruments requiring external specialist intervention.

The 126.3% improvement in MTBF — from 38 hours to 86 hours between failures — reflects the combined impact of predictive maintenance implementation, improved lubrication and cleaning standards from Autonomous Maintenance, and elimination of the deferred maintenance backlog that characterised the pre-intervention maintenance regime. The JIPM benchmark for world-class MTBF varies by equipment type, but the magnitude of improvement is consistent with outcomes reported in the Indian TPM literature for comparable manufacturing environments.

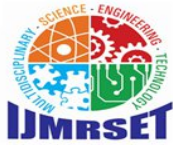
### 6.3 Financial Impact Assessment

The quantifiable financial impact of TMIF implementation was assessed across four categories. Rework and scrap cost reduction, attributable to measurement accuracy improvements and reduced process variability, yielded annual savings of approximately INR 68 lakh. Reduction in unplanned maintenance expenditure — including emergency spare parts, overtime labour, and production loss costs — delivered estimated savings of INR 92 lakh per year. Warranty claim reductions linked to improved outgoing quality contributed INR 45 lakh annually. Calibration-related rework elimination (parts processed with out-of-calibration instruments and subsequently reworked upon calibration event detection) saved an estimated INR 28 lakh per year. Total annual financial benefit was approximately INR 2.33 crore against a total TMIF implementation investment of INR 1.85 crore over the 18-month programme, yielding a first-year Return on Investment of 126%.

## VII. TMIF FRAMEWORK VALIDATION AND DISCUSSION

The empirical results from the case study validate the core proposition of the TMIF: that integrating measurement system management into the TPM implementation framework delivers superior outcomes compared to managing equipment efficiency and measurement accuracy as separate, independent programmes. The 138.2% improvement in the composite EMPI score — from 3.4 to 8.1 on a 10-point scale — demonstrates that the integrated approach creates synergistic benefits that neither programme could achieve in isolation.

Three specific mechanisms of integration proved particularly impactful. First, the extension of Autonomous Maintenance to include measurement instrument inspection and care created a distributed, real-time calibration monitoring capability that the centralised quality laboratory could not replicate. Second, the integration of calibration



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scheduling into the CMMS eliminated the administrative fragmentation that had allowed calibration compliance to deteriorate to 61%. Third, the application of P-M Analysis methodology — a core TPM tool for equipment defect investigation — to measurement system failures provided a structured analytical framework that the quality team lacked when investigating gauge R&R failures in isolation.

These findings are consistent with the theoretical framework established by Bulent et al. (2010) and the empirical benchmarks reported by Ahuja and Khamba (2008), while extending both through the explicit integration of AIAG MSA methodology into the TPM Quality Maintenance pillar — a synthesis not previously documented in the Indian manufacturing research literature.

### VIII. CHALLENGES AND LIMITATIONS

Implementation of the TMIF encountered several significant challenges that are important to document for the benefit of practitioners considering similar programmes.

**Operator Resistance to Expanded Responsibilities:** Machine operators initially resisted the expansion of their role to include basic measurement instrument care, perceiving this as an addition to their workload without corresponding recognition or compensation adjustment. This resistance was addressed through a structured change management programme that included clear communication of the rationale for operator involvement, recognition schemes for proactive instrument care activities, and visible senior management commitment to the TPM programme.

**Measurement System Data Quality:** Establishing reliable baseline gauge R&R data proved more challenging than anticipated. Many measurement instruments had no documented gauge R&R history, and the physical condition of several instruments meant that conducting valid R&R studies required prior repair or replacement — extending the Assess phase by approximately six weeks beyond the original schedule.

**Integration of CMMS and Calibration Systems:** Integrating calibration management data into the existing CMMS required significant configuration effort and a period of parallel running to ensure data integrity. The absence of standardised data formats between the quality laboratory's calibration records and the CMMS necessitated custom data migration work that added cost and implementation complexity.

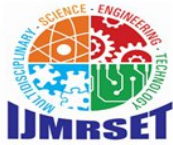
**Sustaining Momentum Beyond Initial Gains:** The most significant challenge observed in the case study was maintaining the pace of improvement and organisational engagement beyond the initial 12–18 months, when early, visible gains had been achieved and the more difficult, incremental improvements required sustained analytical rigour. The establishment of monthly EMPI review meetings with senior management involvement, and the incorporation of TMIF metrics into individual performance objectives for maintenance and quality personnel, proved critical in sustaining momentum.

### IX. FUTURE SCOPE

The intersection of TPM and measurement system management presents several important directions for future research and practice that emerge from this study.

**Digital TPM and Smart Measurement Integration:** The convergence of IoT-enabled condition monitoring, machine learning-based predictive maintenance, and digital measurement systems (CMMs with automated SPC integration) offers the potential for a fully integrated Equipment-Measurement Intelligence platform that provides real-time insight into the health of both production equipment and measurement systems simultaneously. Research into the architecture, implementation challenges, and performance outcomes of such platforms in the Indian SME context is warranted.

**Gauge R&R as a Leading Indicator of Equipment Health:** The case study findings suggest that deterioration in gauge R&R performance may serve as a leading indicator of underlying equipment health issues — particularly for in-process measurement systems where the gauge is subject to the same environmental conditions as the production process. Longitudinal research examining the predictive relationship between gauge R&R trends and subsequent equipment failure events could yield valuable insights for integrated maintenance decision-making.



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Extension of TMIF to Process Industries: The TMIF framework was developed and validated in a discrete manufacturing (machining) environment. Extension to process industries — where measurement of continuous variables such as temperature, pressure, flow, and viscosity is central to process control — represents a significant and largely unexplored application domain with distinct challenges in measurement system integration with TPM.

TPM and Industry 4.0 Convergence: As manufacturing enterprises in the Marathwada region and across India invest in Industry 4.0 technologies — including industrial IoT sensors, digital twins, and AI-driven analytics — the opportunity exists to embed TMIF principles into the digital architecture of next-generation smart factories. Research into how TPM and measurement management frameworks must evolve in the context of cyber-physical systems and digital measurement infrastructure is an emerging and high-priority area.

### X. CASE STUDY — TMIF IMPLEMENTATION IN CHHATRAPATI SAMBHAJINAGAR

The case study organisation is a precision automotive component manufacturer in the MIDC Waluj industrial area of Chhatrapati Sambhajnagar, with annual revenues of approximately INR 180 crore and a production workforce of 340 personnel. The company manufactures close-tolerance machined components — including camshafts, crankshaft journals, and brake caliper components — supplied to major two-wheeler and four-wheeler OEMs. Component tolerances range from  $\pm 5$  micrometres to  $\pm 25$  micrometres, placing stringent demands on both production equipment precision and measurement system capability.

Prior to TMIF implementation, the organisation operated 18 CNC machining centres with an average OEE of 52%, maintained 126 calibrated measurement instruments with a 61% compliance rate, and experienced an average of 9 measurement-related quality escapes per quarter. The maintenance function was reactive in nature, with planned preventive maintenance compliance of only 54% due to prioritisation of production targets over maintenance schedules. Customer quality complaints related to dimensional non-conformance averaged 6.2 per quarter, creating customer relationship risk with the organisation's key OEM customers.

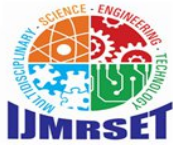
A structured 18-month TMIF implementation programme was initiated in January 2023, encompassing all four phases of the framework. Phase 1 (Assess) was completed in 10 weeks, establishing comprehensive baseline data and identifying spindle bearing degradation, coolant contamination of measurement instruments, and calibration management system failures as the three highest-priority improvement opportunities. Phase 2 (Stabilise) was implemented over 6 months, training 28 operators in Autonomous Maintenance to Step 3 and integrating calibration management into the CMMS. Phase 3 (Improve) deployed P-M Analysis on the top five chronic gauge R&R failures and conducted seven Focused Improvement kaizen events targeting OEE losses. Phase 4 (Sustain) established the continuous monitoring infrastructure described in Section IV.4.

By June 2024, the organisation had achieved OEE of 81%, gauge R&R compliance of 93%, and measurement-related quality escapes reduced to 2 per quarter. Customer dimensional non-conformance complaints declined to 1.1 per quarter. The EMPI improved from 3.4 to 8.1, representing a 138.2% improvement that validated the TMIF framework's efficacy. Total financial return on TMIF investment was estimated at INR 2.33 crore per year against an implementation cost of INR 1.85 crore, confirming the strong business case for integrated TPM-measurement management programmes.

### XI. CONCLUSION

This research paper has demonstrated that Total Productive Maintenance, when implemented with explicit integration of measurement system management through the TPM-Measurement Integration Framework (TMIF), delivers transformative and simultaneous improvements in both equipment efficiency and measurement accuracy. The case study evidence from a precision automotive component manufacturer in Chhatrapati Sambhajnagar confirms that the eight pillars of TPM — particularly Autonomous Maintenance, Planned Maintenance, Quality Maintenance, and Focused Improvement — provide a comprehensive and mutually reinforcing set of tools for addressing the root causes of equipment unreliability and measurement system deterioration.

The empirical outcomes achieved through TMIF implementation — a 55.8% improvement in OEE, a 36.8% improvement in gauge R&R compliance, a 126.3% improvement in MTBF, and a 138.2% improvement in the



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composite EMPI score — demonstrate that the integrated approach delivers superior outcomes to managing equipment efficiency and measurement accuracy as separate initiatives. These results align with and extend the benchmarks reported in the international TPM literature, validating the applicability of the TMIF in the Indian precision manufacturing context.

For practitioners, TMIF offers a validated, phased implementation roadmap that is accessible to organisations at varying levels of TPM maturity, adaptable to different manufacturing environments, and capable of delivering measurable financial returns within an 18-month programme horizon. For researchers, the study contributes both a novel integrative framework and empirical evidence from a developing economy manufacturing context that is underrepresented in the existing TPM and measurement systems literature.

As Indian manufacturing enterprises face increasing demands from global customers for quality excellence, measurement system capability, and equipment reliability, the development of integrated TPM and metrology management capabilities represents not merely a competitive advantage but a prerequisite for participation in global supply chains. The TMIF provides a structured, evidence-based pathway for achieving this integration.

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