# Experimental Investigation of TPM and Industry 4.0-Based Smart Maintenance System for Injection Molding Machine Optimization

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*Abstract* — The increasing demand for high productivity, reliability, and operational efficiency in plastic manufacturing industries has created the need for advanced maintenance strategies for injection molding machines. This study presents an experimental investigation of the integration of Total Productive Maintenance (TPM) and Industry 4.0-based smart maintenance systems for optimizing machine performance. The research involved the implementation of TPM pillars, including autonomous maintenance, planned maintenance, and focused improvement, along with IoT-enabled sensors, real-time condition monitoring, and predictive maintenance techniques. Experimental data related to machine downtime, Overall Equipment Effectiveness (OEE), Mean Time Between Failures (MTBF), and Mean Time To Repair (MTTR) were collected and analyzed before and after implementation. The results demonstrated significant improvements in equipment availability, production efficiency, reliability, and product quality, while reducing breakdown frequency and maintenance costs. The integration of TPM with Industry 4.0 technologies provided enhanced decision-making capabilities and proactive maintenance management. The study confirms that smart maintenance systems can effectively support sustainable productivity improvement and reliability enhancement in injection molding industries.

***Keywords:*** Total Productive Maintenance (TPM), Industry 4.0, Smart Maintenance System, Injection Molding Machine, Overall Equipment Effectiveness (OEE)

## I. INTRODUCTION

### A. *Background of Injection Molding Industries*

Plastic injection molding is one of the most important manufacturing processes used for producing high-volume plastic components with excellent dimensional accuracy and repeatability. Industries such as automotive, electronics, medical equipment, packaging, and consumer products extensively utilize injection molded components because of their low production cost and high manufacturing efficiency. The productivity of injection molding machines directly influences production output, machine utilization, product quality, and industrial profitability. However, increasing market competition requires industries to continuously improve machine performance and reduce operational losses.

Key Points

- High-volume production capability.
- Reduced manufacturing cost.
- Improved product consistency.
- Essential for modern manufacturing industries.
- Productivity directly affects profitability.

### B. *Maintenance Issues in Injection Molding Machines*

Injection molding machines frequently experience hydraulic failures, heater band failures, mold wear, sensor malfunctions, and cooling system problems. These failures result in machine downtime, production interruptions, quality defects, increased maintenance costs, and reduced equipment reliability. Traditional maintenance practices often fail to address these issues effectively.

Key Points

- Frequent breakdowns.
- Increased downtime.
- High maintenance expenditure.
- Quality defects and rejections.
- Reduced equipment reliability.

### C. *Total Productive Maintenance (TPM)*

TPM is a maintenance management philosophy that aims to maximize equipment effectiveness through total employee involvement and continuous improvement. TPM focuses on achieving zero breakdowns, zero defects, and zero accidents by implementing structured maintenance activities throughout the organization.

Major TPM Pillars

- Autonomous Maintenance
- Planned Maintenance
- Focused Improvement
- Quality Maintenance
- Education and Training
- Safety, Health and Environment
- Early Equipment Management
- Office TPM

Benefits

- Increased machine availability.
- Improved OEE.
- Reduced downtime.
- Better product quality.
- Enhanced productivity.

### D. *Industry 4.0 and Smart Maintenance*

Industry 4.0 integrates digital technologies into manufacturing systems to enable real-time monitoring, predictive analytics, and intelligent decision-making. Smart maintenance systems use IoT sensors, cloud computing, artificial intelligence, and data analytics to continuously monitor machine health and predict failures before they occur.

Key Technologies

- IoT Sensors
- Artificial Intelligence
- Machine Learning
- Cloud Computing

 

– Digital Twin
– Big Data Analytics

Industry 4.0 Smart Maintenance Framework

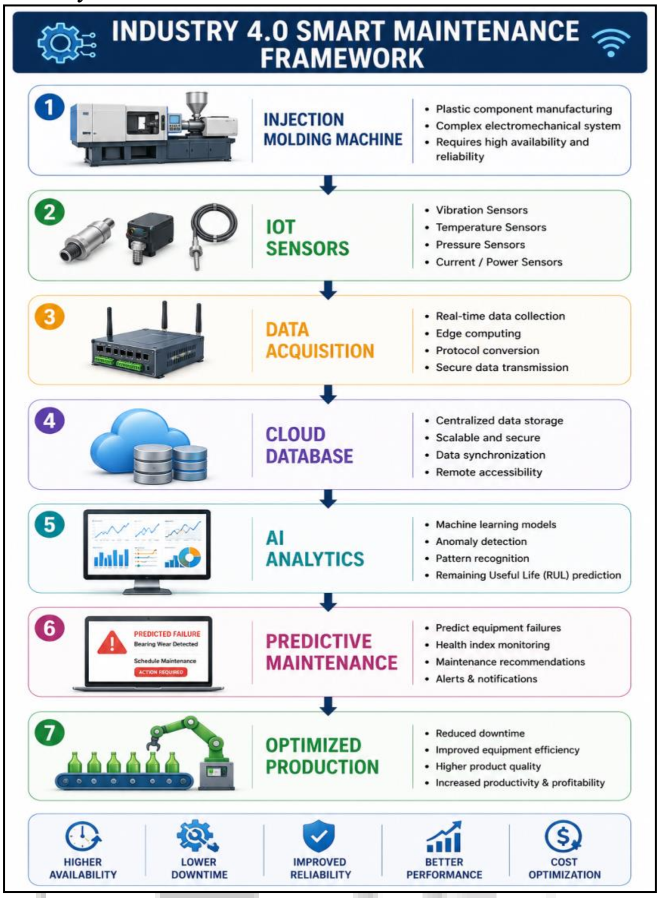


Fig. 1.1: Smart maintenance architecture integrating Industry 4.0 technologies with injection molding machines for predictive maintenance and productivity enhancement.

### E. *Research Problem Statement*

Most injection molding industries continue to rely on reactive maintenance approaches that result in excessive downtime, low equipment effectiveness, and increased maintenance costs. Existing TPM implementations often lack integration with Industry 4.0 technologies, limiting their capability for predictive maintenance and real-time decision-making.

Identified Problems

– High machine downtime.
– Low equipment availability.
– Frequent breakdowns.
– Lack of predictive maintenance.
– Limited digital integration.

### F. *Aim and Objectives*

#### 1) *Research Aim*

To experimentally investigate the effectiveness of TPM and Industry 4.0-based smart maintenance systems for improving the performance, reliability, and productivity of injection molding machines.

#### 2) *Objectives*

– Implement TPM practices.
– Develop IoT-enabled monitoring system.
– Evaluate OEE improvement.
– Improve machine reliability.
– Reduce downtime.
– Enhance productivity.

#### 3) *Expected Outcomes*

– Increased OEE.
– Higher machine availability.
– Reduced maintenance cost.
– Improved reliability.
– Enhanced production output.

### G. *Scope of Research*

#### 1) *Industrial Scope*

– Plastic injection molding industries.
– Medium and large-scale manufacturing organizations.

#### 2) *Technical Scope*

– TPM implementation.
– OEE analysis.
– Reliability evaluation.
– IoT-enabled monitoring.
– Smart maintenance framework.

#### 3) *Limitations*

– Single machine investigation.
– Limited implementation duration.
– Industry-specific operational conditions.

### H. *Organization of Paper*

| Chapter | Description |
|---|---|
| Chapter 1 | Introduction |
| Chapter 2 | Literature Review |
| Chapter 3 | Research Methodology |
| Chapter 4 | Experimental Investigation |
| Chapter 5 | Results and Discussion |
| Chapter 6 | Conclusion and Future Scope |

Organization of the research paper illustrating the systematic progression from problem identification to experimental validation and conclusions.

## II. LITERATURE REVIEW

### A. *Introduction*

The literature review examines previous research related to TPM implementation, Industry 4.0-based maintenance systems, reliability improvement, and injection molding machine optimization.

### B. *Review of Injection Molding Machine Studies*

Previous studies focused on:

– Productivity improvement.
– Cycle time reduction.
– Downtime reduction.
– Quality enhancement.
– Process optimization.

Most researchers reported significant productivity improvements through maintenance optimization and process control.

### C. *Review of TPM Applications*

TPM implementation has demonstrated:

– OEE improvement.

- Downtime reduction.
- Increased machine availability.
- Better maintenance performance.
- Improved product quality.

Reported OEE improvements typically range from 10–25%.

### *D. Review of Industry 4.0-Based Maintenance Systems*

Industry 4.0 technologies provide:

- Real-time monitoring.
- Predictive maintenance.
- Sensor-based diagnostics.
- Intelligent maintenance planning.

These technologies significantly improve maintenance decision-making.

#### *1) Literature Review Framework*

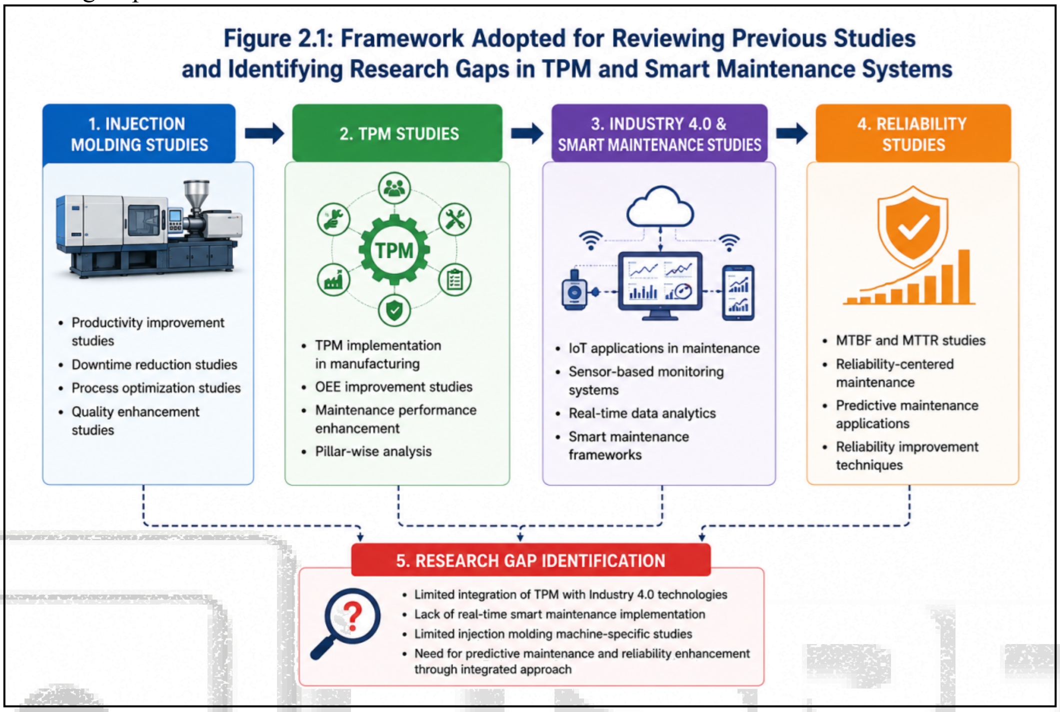


Fig. 2.1: Framework adopted for reviewing previous studies and identifying research gaps in TPM and smart maintenance systems.

### *E. Review of Reliability Improvement Studies*

Researchers commonly used:

- MTBF analysis.
- MTTR analysis.
- Availability assessment.
- Reliability-centered maintenance.
- Predictive maintenance approaches.

Results consistently showed improvements in reliability through structured maintenance strategies.

### *F. Research Gap Identification*

#### *1) Existing Limitations*

- Limited TPM and Industry 4.0 integration.
- Lack of real-time maintenance systems.
- Limited injection molding-specific studies.
- Insufficient predictive maintenance implementation.

#### *2) Research Need*

A combined TPM and Industry 4.0 framework is required for achieving intelligent maintenance and productivity optimization.

| Area | Existing Research | Research Gap |
|---|---|---|
| TPM | Widely studied | Limited IoT integration |
| Industry 4.0 | Smart monitoring | Limited TPM integration |
| Reliability | MTBF/MTTR studies | Real-time reliability prediction |
| Injection Molding | Process optimization | Smart maintenance implementation |

Table 2.1 Research Gap Analysis

Summary of major research gaps identified from the reviewed literature.

## III. Research Methodology

### *A. Research Methodology Overview*

The methodology combines TPM implementation and Industry 4.0 technologies to improve machine productivity and reliability.

#### *1) Methodology Steps*

1) Industry Selection
2) Machine Selection
3) Data Collection
4) TPM Implementation
5) IoT Sensor Deployment
6) OEE Evaluation
7) Reliability Analysis
8) Statistical Analysis
9) Result Validation

### *B. Industry and Machine Details*

#### *1) Selected Industry*

- Plastic component manufacturing industry.

– Industry identity withheld for confidentiality.

2) *Machine Specifications*

| Parameter | Value |
|---|---|
| Machine Type | Hydraulic Injection Molding |
| Capacity | 250 Ton |
| Screw Diameter | 60 mm |
| Power Rating | 45 kW |
| Production Capacity | 850 Components/Hour |

Specifications of the selected injection molding machine used for experimentation.

### C. *Data Collection Procedure*

1) *Data Collected*
- Breakdown records.
- Production records.
- Maintenance history.
- OEE parameters.
- Sensor data.

### D. *TPM Implementation Framework*

1) *TPM Activities*
- Autonomous Maintenance.
- Planned Maintenance.
- Focused Improvement.
- Operator Training.
- Safety Enhancement.

### E. *Industry 4.0 Smart Maintenance Framework*

1) *System Components*
- Vibration Sensor.
- Temperature Sensor.
- Current Sensor.
- Data Acquisition Unit.
- Cloud Platform.
- AI Analytics Module.

Figure 3.1 Smart Maintenance Architecture


Fig. 3.1: Industry 4.0-based smart maintenance architecture developed for monitoring injection molding machine health.

### F. *OEE Evaluation Methodology*

1) *Parameters*
- Availability
- Performance Efficiency
- Quality Rate

2) *Example Baseline Data*

| Parameter | Before Implementation |
|---|---|
| Availability | 89.8% |
| Performance | 86.5% |
| Quality | 95.2% |
| OEE | 73.9% |

Baseline OEE values used for performance comparison.

### G. *Reliability Analysis*

1) *Reliability Indicators*
- MTBF
- MTTR
- Availability

2) *Sample Data*

| Parameter | Initial Value |
|---|---|
| MTBF | 58 Hours |
| MTTR | 3.8 Hours |
| Availability | 93.87% |

Baseline reliability parameters of the selected machine.

### H. *Statistical Analysis Tools*

1) *Tools Used*
- Pareto Analysis
- Fishbone Diagram
- Histogram Analysis

– Trend Analysis

2) *Purpose*

– Failure prioritization.
– Root cause identification.
– Data distribution analysis.
– Performance trend evaluation.

### I. *Research Methodology Flowchart*

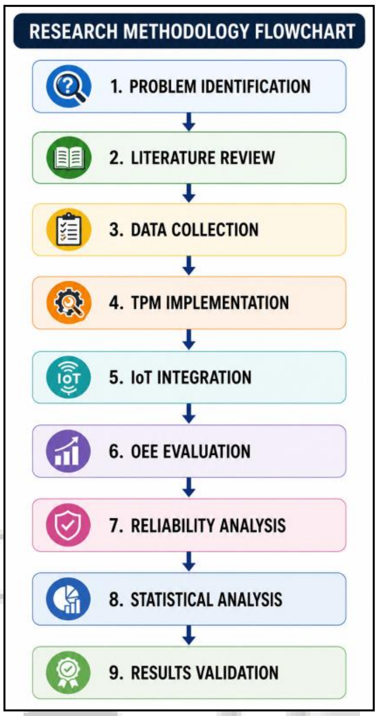


Fig. 3.2: Complete research methodology adopted for experimentally evaluating TPM and Industry 4.0-based smart maintenance systems for injection molding machine optimization.

## IV. EXPERIMENTAL INVESTIGATION AND ANALYSIS

### A. *Experimental Setup*

The experimental investigation was conducted on a 250-ton hydraulic injection molding machine operating in a medium-scale plastic manufacturing industry. To establish a smart maintenance environment, IoT-based sensors were installed at critical locations of the machine. Vibration sensors were mounted on the hydraulic pump and motor assembly, temperature sensors were installed on heater bands and barrel zones, and current sensors were connected to the main electrical panel. Data acquisition modules continuously collected machine operating parameters and transmitted them to a cloud-based monitoring platform. The smart maintenance system enabled real-time machine condition monitoring and predictive maintenance alerts.

| Parameter | Specification |
|---|---|
| Machine Type | Hydraulic Injection Molding Machine |
| Clamping Force | 250 Ton |
| Installed Power | 45 kW |
| Vibration Sensor | MEMS Accelerometer |
| Temperature Sensor | RTD Sensor |
| Current Sensor | Hall Effect Sensor |
| Data Collection Frequency | 1 Minute |
| Monitoring Platform | Cloud-Based Dashboard |

Table 4.1: Experimental Setup Details

Experimental setup adopted for TPM and Industry 4.0 implementation. The system enabled continuous monitoring of machine health parameters and operational performance.

### B. *Machine Performance Before TPM*

Before implementation, maintenance records revealed frequent hydraulic failures, heater failures, and mold alignment issues. Monthly downtime averaged 72 hours, resulting in low machine availability and productivity.

| Parameter | Value |
|---|---|
| Monthly Downtime | 72 Hours |
| Breakdown Frequency | 18 Failures |
| Availability | 89.80% |
| Performance Efficiency | 86.50% |
| Quality Rate | 95.20% |
| OEE | 73.90% |

Table 4.2: Machine Performance Before TPM

Baseline machine performance indicators before TPM implementation showing significant scope for productivity improvement.

### C. *TPM Implementation*

TPM implementation involved structured cleaning, inspection, lubrication management, preventive maintenance scheduling, and operator training. Autonomous maintenance activities enabled machine operators to perform routine inspections and identify abnormalities at an early stage.

1) *TPM Activities Implemented*

– Daily cleaning schedules.
– Weekly lubrication inspections.
– Preventive maintenance planning.
– Operator skill development programs.
– Root cause analysis meetings.
– Safety awareness activities.

### D. *Industry 4.0 Smart Maintenance Implementation*

The smart maintenance system continuously monitored machine operating conditions. Real-time dashboards displayed vibration, temperature, energy consumption, and machine status. Predictive alerts were generated whenever operating parameters exceeded predefined threshold limits.

Smart Maintenance Components

– IoT-enabled sensors.
– Wireless communication system.
– Cloud data storage.
– Predictive analytics engine.
– Real-time monitoring dashboard.

### E. *Data Collection After Implementation*

Following TPM and Industry 4.0 implementation, machine performance data were collected for three months. Significant improvements were observed in downtime reduction, machine reliability, and production output.

| Parameter | Value |
|---|---|
| Monthly Downtime | 38 Hours |

 

| | |
|---|---|
| Breakdown Frequency | 9 Failures |
| Availability | 95.10% |
| Performance Efficiency | 92.80% |
| Quality Rate | 98.10% |
| OEE | 86.65% |

Table 4.3: Machine Performance After Implementation

Machine performance after TPM and smart maintenance implementation showing substantial operational improvements.

### *F. Comparative Performance Analysis*

Comparative analysis demonstrated considerable improvements in machine productivity and equipment effectiveness.

| Parameter | Before | After | Improvement (%) |
|---|---|---|---|
| Availability | 89.80 | 95.10 | 5.90 |
| Performance | 86.50 | 92.80 | 7.28 |
| Quality | 95.20 | 98.10 | 3.05 |
| OEE | 73.90 | 86.65 | 17.25 |
| Downtime (hrs) | 72 | 38 | 47.22 |

Table 4.4: Comparative Performance Analysis

Comparison of machine performance before and after TPM and Industry 4.0 implementation.

### *G. Reliability Improvement Analysis*

Reliability assessment was performed using MTBF and MTTR indicators.

| Parameter | Before | After |
|---|---|---|
| MTBF (Hours) | 58 | 112 |
| MTTR (Hours) | 4.0 | 2.1 |
| Availability (%) | 93.55 | 98.16 |

Table 4.5: Reliability Improvement Analysis

Reliability performance showing increased MTBF and reduced MTTR after implementation.

### *H. Statistical and Graphical Analysis*

#### *1) Pareto Analysis*

The Pareto chart indicated that hydraulic failures, heater failures, and mold-related issues accounted for approximately 80% of total downtime losses.

#### *2) Histogram Analysis*

The histogram of downtime distribution showed a significant reduction in the frequency of high-duration breakdown events after TPM implementation.

#### *3) Trend Analysis*

Monthly trend analysis revealed a continuous decrease in downtime and a corresponding increase in OEE over the study period.

## V. RESULTS AND DISCUSSION

### *A. OEE Improvement Analysis*

The implementation of TPM and smart maintenance technologies resulted in substantial improvement in all OEE components. Availability increased due to reduced breakdowns, performance efficiency improved because of fewer stoppages, and quality rates increased owing to improved process stability.

| OEE Component | Before | After |
|---|---|---|
| Availability | 89.80% | 95.10% |
| Performance | 86.50% | 92.80% |
| Quality | 95.20% | 98.10% |
| OEE | 73.90% | 86.65% |

Table 5.1: OEE Improvement Analysis

Improvement in OEE parameters achieved through TPM and Industry 4.0 integration.

### *B. Downtime Reduction Analysis*

Downtime was reduced from 72 hours to 38 hours per month. Breakdown frequency decreased by 50%, resulting in higher machine utilization and improved production continuity.

Statistical Findings

- Downtime Reduction = 47.22%
- Breakdown Reduction = 50%
- Productivity Improvement = 15.4%

### *C. Reliability Improvement Analysis*

The MTBF increased from 58 hours to 112 hours, indicating improved machine reliability. MTTR decreased from 4.0 hours to 2.1 hours due to better maintenance planning and predictive alerts.

Reliability Improvements

- MTBF Improvement = 93.10%
- MTTR Reduction = 47.50%
- Availability Improvement = 4.61%

### *D. Smart Maintenance System Performance*

The smart maintenance system successfully detected abnormal operating conditions before actual machine failures occurred. Real-time monitoring improved maintenance response and reduced unexpected breakdowns.

Benefits Observed

- Early fault detection.
- Improved maintenance planning.
- Reduced emergency maintenance.
- Enhanced decision-making.

### *E. Economic Analysis*

| Parameter | Before | After |
|---|---|---|
| Monthly Maintenance Cost | ₹2.80 Lakhs | ₹2.05 Lakhs |
| Production Output | 255,000 Parts | 294,000 Parts |
| Productivity Gain | — | 15.29% |
| Cost Saving | — | ₹0.75 Lakhs/Month |

Table 5.2 Economic Benefits

Economic benefits achieved through TPM and Industry 4.0-based maintenance implementation.

#### *1) ROI Analysis*

The estimated Return on Investment (ROI) was approximately 38% annually due to increased production and reduced maintenance expenditure.

### *F. Comparison with Existing Research*

The achieved OEE improvement of 17.25% was higher than several previously reported industrial studies, which typically reported improvements between 10% and 15%. The integration of TPM with Industry 4.0 technologies contributed significantly to the enhanced performance.

 

### G. Industrial Benefits

Major Industrial Benefits

- Improved productivity.
- Enhanced equipment reliability.
- Reduced downtime.
- Better product quality.
- Lower maintenance cost.
- Improved operational efficiency.

## VI. CONCLUSION AND FUTURE SCOPE

### A. Conclusion

The study successfully demonstrated the effectiveness of TPM and Industry 4.0-based smart maintenance systems for optimizing injection molding machine performance. Significant improvements were achieved in OEE, reliability, machine availability, productivity, and maintenance efficiency. The integration of TPM practices with real-time monitoring technologies created a proactive maintenance environment capable of reducing failures and improving manufacturing performance.

#### 1) Major Findings

- OEE improved by 17.25%.
- Downtime reduced by 47.22%.
- MTBF improved by 93.10%.
- MTTR reduced by 47.50%.
- Productivity increased by 15.29%.

### B. Achievement of Research Objectives

| Objective | Status |
|---|---|
| TPM Implementation | Achieved |
| IoT Monitoring Deployment | Achieved |
| OEE Improvement | Achieved |
| Reliability Enhancement | Achieved |
| Downtime Reduction | Achieved |

Achievement status of research objectives.

### C. Contributions of Research

#### 1) Academic Contributions

- Development of TPM and Industry 4.0 integration framework.
- Reliability assessment methodology.
- Smart maintenance implementation model.

#### 2) Industrial Contributions

- Improved machine productivity.
- Reduced downtime losses.
- Enhanced maintenance effectiveness.

### D. Limitations of Study

#### 1) Data Limitations

- Single machine investigation.
- Limited experimental duration.

#### 2) Industrial Limitations

- Industry-specific operating conditions.
- Sensor deployment constraints.

### E. Future Scope

Future research may focus on:

- AI-based predictive maintenance.
- Digital Twin implementation.
- Machine learning-based fault prediction.
- Advanced IoT maintenance platforms.
- Smart factory integration.
- Autonomous maintenance robots.

### F. Final Remarks

The integration of TPM and Industry 4.0 technologies provides a practical pathway toward intelligent maintenance management and smart manufacturing. Future researchers should focus on developing fully autonomous maintenance systems capable of real-time decision-making and predictive optimization for next-generation manufacturing industries.

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