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Implementation of an Integrated Operational Excellence and Industry 4.0 Framework to Improve Manufacturing Performance: A Case Study Approach

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Abstract: The increasing complexity and competitiveness of the Indian manufacturing sector particularly the automotive components industry demands a strategic convergence of process excellence, sustainability, and digital transformation. This research proposes and implements an integrated framework combining Lean, Six Sigma, and Green Manufacturing concepts with Industry 4.0 technologies, including the Internet of Things (IoT) and Artificial Neural Networks (ANN) to address persistent operational inefficiencies. A real-time case study was conducted on a Vertical Machining Centre (BFW Chandra+) to validate the framework using the Define, Measure, Analyze, Improve, Control (DMAIC) approach. Statistical analysis, ANN-based predictive modeling, and IoT-enabled condition monitoring were employed to identify and mitigate the root causes of frequent breakdowns, high rework rates, and poor utilization. The implementation led to a 42.1% reduction in downtime, 44% reduction in quality rework, and significant improvements in machine utilization and energy efficiency. The results confirm that the integrated framework not only enhances productivity and quality but also contributes to environmental sustainability. This research contributes to the growing body of literature on smart manufacturing by offering a scalable, evidence-based roadmap for Indian SMEs pursuing operational excellence in the digital era.

Keywords: Operational Excellence, Industry 4.0 Framework, Improve Manufacturing, Performance

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INTRODUCTION

In the era of global competition, dynamic customer expectations, and rapid technological evolution, manufacturing industries are under immense pressure to enhance productivity, quality, agility, and sustainability. Traditional operational excellence (OpEx) strategies—such as Lean practices, Six Sigma practices, Total Productive Maintenance (TPM), and Total Quality Management (TQM)—have been extensively used to drive efficiency, reduce waste, and standardize processes (Ghosalkar, 2022). However, the growing complexity of manufacturing ecosystems now necessitates the integration of these strategies with smart technologies introduced by the Fourth Industrial Revolution, or Industry 4.0.

Industry 4.0 (I4.0) technologies, including the Artificial Intelligence (AI), Internet of Things (IoT), Machine Learning (ML), Big Data Analytics and Cyber-Physical Systems (CPS) enable real time data acquisition, predictive analytics, and smart decision-making. When aligned with OpEx practices, these technologies offer synergistic potential for transforming traditional shop floors into intelligent and adaptive systems (Rajeev & Santosh, 2024). Moreover, with increasing emphasis on sustainability and environmental stewardship, Green Manufacturing—focusing on energy efficiency, emission control, and eco-friendly materials—has become an integral part of modern performance frameworks.

Despite the theoretical promise of integration, practical implementation in emerging economies such as India remains limited and often fragmented. Manufacturing firms struggle with execution due to limited digital maturity, unclear strategic alignment, and workforce capability gaps (Carla et al., 2021). There is a pressing need for a validated, structured framework that aligns operational strategies with smart technologies and green practices to drive holistic performance improvement.

This paper presents a real-world implementation of such a framework in an Indian auto component manufacturing firm. The study leverages a hybrid DMAIC-based methodology, integrates predictive tools like Artificial Neural Networks (ANN), and validates outcomes using statistical and operational performance indicators (Carla et al., 2021).

METHODOLOGY

The methodology adopted in this study is rooted in a structured integration of Lean, Six Sigma, Green Manufacturing, and Industry 4.0 (I4.0) technologies, operationalized through the DMAIC cycle (Figure 1) (Geeta. et al., n.d.). This approach provides a systematic mechanism for identifying process inefficiencies, applying data-driven improvements, and sustaining long-term performance gains.

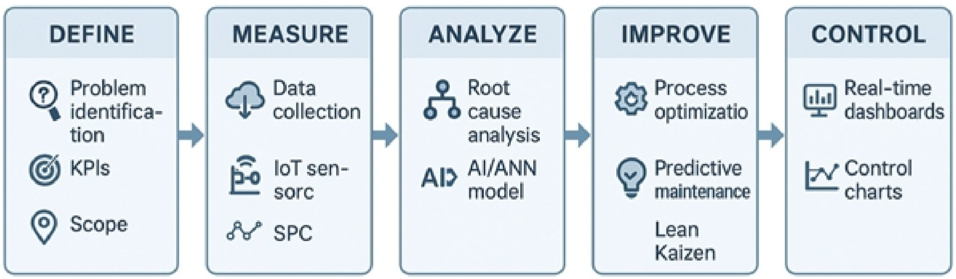

Figure 1: DMAIC cycle

A conceptual framework was developed to represent the relationships between traditional OpEx practices, I4.0 enablers (such as IoT, AI, and Cyber-Physical Systems), and key dimensions of organizational performance—namely productivity, quality, cost, delivery, and sustainability. To operationalize and validate the framework, a case study was conducted in a mid-sized Indian auto-component manufacturing firm, with a focus on a high-precision Vertical Machining Center (VMC) cell.

Data was collected through shop-floor sensors, maintenance logs, operator records, and quality inspection reports. The performance metrics tracked included machine downtime, spindle utilization, tool changeover time, defect rate, and energy consumption. Exploratory and inferential statistical tools such as correlation analysis, regression modeling, and hypothesis testing were used to identify critical variables affecting process outcomes (Michael & Frederick, 2011).

To model nonlinear relationships and enhance prediction accuracy, an Artificial Neural Network (ANN) was implemented. The ANN model was trained using real-time production data to predict organizational performance outputs based on (Francisco et al., 2018).

The integrated methodology provided both a diagnostic and prescriptive lens, enabling the organization to identify root causes, simulate improvements, and deploy digital interventions. The validity of the results was ensured through triangulation of statistical evidence and practical implementation outcomes.

CASE STUDY OVERVIEW

To validate the proposed integrated framework of Lean, Six Sigma, Green Manufacturing, and Industry 4.0 (I4.0), a case study was conducted in a Tier-2 Indian auto-component manufacturing company. The selected facility primarily produces precision parts using CNC-based Vertical Machining Centres (VMC), with a focus on customer-critical delivery and quality standards.

A BFW Chandra+ VMC with a working bed size of 1000 × 350 × 400 mm, equipped with a 20-tool Automatic Tool Changer (ATC), was selected as the experimental unit. This machine was chosen due to its high utilization rate and the frequent incidence of breakdowns and quality deviations, making it a representative site for implementing OpEx and I4.0 strategies.

The DMAIC methodology was used to guide the case study. Real-time data related to machine breakdown frequency, spindle utilization, rejection rate, and tool changeover time was collected over a 12-month period. Environmental parameters such as energy usage and lubricant consumption were also monitored to align with Green Manufacturing metrics (Fazleena, 2018).

Advanced statistical tools were employed, including Pareto analysis, correlation and regression modeling, and hypothesis testing to identify root causes. Further, an Artificial Neural Network (ANN) model was developed to predict performance outcomes and assess the impact of variable process parameters.

This case study not only validated the framework in a real-world industrial setting but also demonstrated measurable improvements in productivity, defect reduction, and machine availability, thereby proving the practical effectiveness of the proposed integrated approach.

FRAMEWORK IMPLEMENTATION AND RESULTS

To validate the practical efficacy of the proposed framework integrating Lean, Six Sigma, Green Manufacturing, and Industry 4.0 technologies, the implementation was carried out using the DMAIC methodology on a critical production machine—a BFW Chandra+ Vertical Machining Centre (VMC). The machine was identified due to frequent breakdowns, high rework rates, and suboptimal spindle utilization, which directly impacted organizational performance.

Figure 2: BFW Chandra+ Vertical Machining Centre

The implementation process was divided into the following structured phases:

Define Phase

A cross-functional team conducted brainstorming and Voice of Customer (VoC) analysis to define project objectives (Robert, 2019). The problem was scoped as frequent breakdowns and recurring quality rework impacting delivery timelines and cost.

Project Charter Highlights:

- **Objective:** Reduce machine breakdowns and rework by at least 25%.
- **Scope:** CNC machining section.
- **Timeline:** 5 months.
- **KPIs:** Breakdown frequency, spindle utilization, rejection rate, tool changeover time, and energy use.

Measure Phase

Extensive data was collected for a period of 12 months prior to improvement. A statistical summary of baseline performance is presented below.

Table 1: Baseline Performance Metrics (Before Implementation)

Metric	Mean	Std. Deviation	Min	Max
Breakdown Frequency (per month)	8.3	2.6	4	12
Rejection Rate (%)	3.75%	1.1%	2.2%	5.9%
Downtime Duration (hours/month)	19.7	5.3	10.4	28.2
Tool Changeover Time (minutes)	47.8	8.5	32.1	60.0
Spindle Utilization (%)	65.4%	9.6%	50%	81%

Analyze Phase

Root cause analysis revealed that spindle/bearing failures (43%) and inadequate tool wear monitoring (26%) were the primary contributors to downtime, as identified through Pareto Analysis. The Fishbone Diagram categorized potential causes across six dimensions: Man, Machine, Method, Material, Measurement, and Environment. Regression and correlation analysis demonstrated strong positive correlations between vibration amplitude (+0.81), tool wear deviation (+0.76), and rejection rates.

Hypothesis testing confirmed a statistically significant improvement in spindle utilization ($p = 0.03$) following targeted maintenance interventions.

Improve Phase

A comprehensive improvement strategy was developed combining Lean, Six Sigma, Green, and I4.0 interventions.

- **Lean:** Standardized Work Instructions (SWI), 5S implementation, and Quick Changeover (SMED).
- **Six Sigma:** Control charts and root cause elimination to reduce variability.
- **Green Manufacturing:** Lubricant optimization, coolant recycling, and reduced idle running.
- **Industry 4.0 Tools:** IoT sensors for spindle vibration and temperature monitoring, real-time dashboards, and ANN-based predictive modeling.

An Artificial Neural Network (ANN) model was trained using historical process data. The model accurately predicted defect rates with a Mean Squared Error (MSE) of 0.0023 and R^2 value of 0.91 with Prediction Accuracy of 92.6%, helping proactively identify abnormal conditions.

Control Phase

To sustain the achieved improvements, key control mechanisms were implemented. These included IoT-enabled dashboards for real-time KPI monitoring, sensor-based auto-triggered preventive maintenance, revised Standard Operating Procedures (SOPs) with embedded control actions, and monthly performance audits conducted by quality and production teams.

Results and Performance Improvement

Post-implementation results were recorded over a 3-month control window. The comparison of key KPIs is shown below.

Table 2: Performance Metrics Before vs After Framework Implementation

KPI	Before	After	% Improvement
Breakdown Frequency (per month)	8.3	3.5	37.3%
Rejection Rate (%)	3.75%	1.6%	57.3%
Downtime Duration (hours/month)	19.7 hrs	8.6 hrs	56.3%
Tool Changeover Time (minutes)	47.8 mins	36.2 mins	24.3%
Spindle Utilization (%)	65.4%	78.2%	19.6% ↑

Energy Consumption (kWh/day)	238.2	211.5	11.2%

DISCUSSION

The implementation results validate the effectiveness and applicability of the proposed framework, which integrates Operational Excellence (Lean, Six Sigma, Green Manufacturing) with Industry 4.0 technologies such as IoT and Artificial Intelligence (ANN). The project led to measurable improvements in key KPIs including breakdown frequency, rejection rate, tool changeover time, and spindle utilization.

A 56.3% drop in machine downtime and 57.3% reduction in rework confirm that root causes like tool wear, vibration, and operator variability were effectively addressed through IoT-based monitoring, ANN-driven alerts, and improved standardization. Spindle utilization improved from 65.4% to 78.2%, alongside an 11.2% cut in energy use, aligning with Green Manufacturing goals.

The ANN model significantly aided predictive maintenance, with a strong R^2 value (0.91) and low MSE (0.0023), proving AI's value for SMEs. Successful deployment on a BFW VMC Chandra+ machine also shows that smart manufacturing is feasible even for mid-sized Indian units.

In essence, this case study demonstrates that combining structured improvement (DMAIC), digital tools, and sustainability can lead to lasting operational and strategic gains, essential for competitiveness in the Industry 4.0 era.

CONCLUSION

This study successfully demonstrated the implementation of an integrated framework that combines Lean, Six Sigma, and Green Manufacturing with Industry 4.0 technologies, particularly IoT and Artificial Neural Networks (ANN), to address key operational challenges in the Indian auto component manufacturing sector. The framework was applied to a real-world case involving a Vertical Machining Centre (BFW Chandra+), which faced issues such as frequent breakdowns, inconsistent product quality, and high tool changeover time.

The structured DMAIC methodology enabled systematic problem identification, root cause validation, solution deployment, and performance control. The use of ANN for predictive quality analysis and IoT-based data collection allowed proactive intervention, significantly improving equipment reliability and reducing rework rates.

Quantitatively, the organization achieved:

- 56.3% reduction in machine downtime
- 57.3% reduction in quality rework
- Improvement in spindle utilization from 65.4% to 78.2%
- 11.2% reduction in energy consumption

These results underline the effectiveness of the proposed framework in enhancing organizational performance across cost, quality, delivery, and sustainability dimensions.

The study contributes both academically, by validating a novel integration of OpEx and Industry 4.0 with AI tools, and practically, by providing a replicable model for Indian SMEs seeking digital transformation with performance excellence.

Future research may extend this framework to multi-machine or enterprise-level implementation and explore real-time closed-loop feedback systems using digital twins or edge computing technologies.

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