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Original Article

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Integrating Lean Six Sigma and Industry 4.0 to Enhance Manufacturing Productivity in India

Navneet Kumar [a,*] and Sachin Saini [a]

[a] Department of Mechanical Engineering, Faculty of Engineering, RIMT University, Mandi Gobindgarh, Punjab 147301, India.
* Correspondence: principalpattamehlog@gmail.com (N.K.)

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Abstract

Small and medium-scale manufacturing enterprises (SMEs) in India face increasing competitive pressure due to rising material costs, stringent quality standards, and limited operational resources. Enhancing productivity while maintaining cost efficiency and delivery reliability remains a significant challenge. This study investigates the impact of integrating Lean Six Sigma (LSS), Total Productive Maintenance (TPM), selective Industry 4.0 technologies, and energy management practices to improve manufacturing performance in an Indian transformer manufacturing SME. Using a structured case study approach, the research implemented a phased Operational Excellence (OPEX) framework over a six-month period. Value Stream Mapping identified process bottlenecks and excessive non-value-added time, while Six Sigma tools addressed quality variation in the coil winding process. TPM initiatives improved equipment reliability, and a low-cost IoT vibration sensor enabled predictive maintenance. Additionally, an energy audit guided targeted efficiency improvements. The results demonstrate substantial performance gains: production lead time decreased by 28.6% (from 28 to 20 days), coil winding defects were reduced by 60% (from 8.5% to 3.4%), on-time delivery improved from 55% to 85%, Overall Equipment Effectiveness increased by 35% (from 52% to 70.2%), and energy cost per unit declined by 20%. The findings confirm that a pragmatic, integrated OPEX framework can deliver multidimensional productivity gains without requiring large-scale capital investment. This study contributes to the manufacturing and operations management literature by providing empirical evidence that selective Industry 4.0 adoption can effectively complement Lean Six Sigma in SME environments, offering a scalable pathway to sustainable, digitally enabled manufacturing excellence.

1. Introduction

The global electrical transformer manufacturing industry operates in an increasingly challenging environment characterized by intense market competition, volatile raw material prices, stringent regulatory standards, and rising customer expectations for quality and delivery reliability. These pressures are particularly pronounced in emerging economies such as India, where small and medium-scale enterprises (SMEs) constitute a significant portion of the manufacturing ecosystem and play a vital role in industrial growth, employment generation, and supply chain resilience. Despite their importance, transformer manufacturing SMEs often struggle with limited financial resources, inadequate technological infrastructure, and persistent operational inefficiencies, leading to high levels of waste, rework, downtime, and quality variability (Jou et al., 2024; Prashar, 2018).

Enhancing manufacturing productivity has therefore become a strategic imperative for SMEs seeking long-term sustainability and competitiveness. However, productivity improvement in this sector is constrained by fragmented production systems, low process visibility, equipment-related failures, and a lack of standardized problem-solving practices. Traditional improvement initiatives are often reactive rather than systematic, yielding incremental gains that are difficult to sustain over time. As a result, SMEs increasingly recognize the need for structured operational frameworks that can simultaneously address efficiency, quality, cost, and delivery performance.

Operational Excellence (OPEX) methodologies, particularly Lean Manufacturing and Six Sigma, have been widely adopted in large-scale industries to eliminate non-value-added activities, reduce process variability, and enhance overall performance. Lean Manufacturing focuses on waste reduction and flow optimization, while Six Sigma emphasizes defect reduction through data-driven decision-making. Despite their proven effectiveness, the adoption of these methodologies among SMEs remains limited, largely due to perceptions of complexity, high implementation costs, skill shortages, and resistance to organizational change (Panayiotou et al., 2022; Xiang & Chin, 2021). Nevertheless, emerging empirical evidence suggests that when these methodologies are adapted to the SME context and implemented in an integrated manner, they can generate substantial operational and financial benefits (Saini & Singh, 2022; Gaikwad & Sunnapwar, 2024).

In parallel, the advent of Industry 4.0 has introduced advanced digital technologies—such as the Internet of Things (IoT), cyber-physical systems, data analytics, and predictive maintenance—that offer new opportunities to enhance manufacturing performance. While full-scale digital transformation may be impractical for resource-constrained SMEs, selective and strategic adoption of Industry 4.0 tools has been shown to complement traditional OPEX practices by improving process transparency, equipment reliability, and decision-making capabilities (Antony et al., 2022; Çınar et al., 2020). In particular, IoT-enabled predictive maintenance enables early detection of equipment failures, thereby reducing unplanned downtime and supporting continuous improvement initiatives.

Recent research increasingly advocates integrating Lean Six Sigma with Industry 4.0 technologies as a holistic approach to productivity enhancement. Lean Six Sigma provides the structured methodology and problem-solving discipline, while Industry 4.0 technologies supply real-time data and advanced analytical capabilities to sustain improvements. Tools such as Value Stream Mapping facilitate the identification of process bottlenecks and waste (Seth et al., 2017), Total Productive Maintenance strengthens equipment effectiveness and operator involvement (Sharma et al., 2006), and predictive analytics enhances maintenance planning and operational reliability (Badawi et al., 2022). However, empirical studies demonstrating the integration of such frameworks within SME contexts, particularly in the Indian transformer manufacturing sector, remain limited.

Against this backdrop, the present study addresses this research gap by examining the implementation of an integrated Lean Six Sigma and Industry 4.0 framework in an Indian transformer manufacturing SME, referred to as “ABC Transformers.” By combining Value Stream Mapping, Total Productive Maintenance, Lean Six Sigma tools, and IoT-based predictive analytics, the study aims to demonstrate how a pragmatic and context-specific integration of traditional OPEX methodologies and digital technologies can deliver measurable improvements in manufacturing productivity, quality performance, and operational stability (Dweiri & Ishaq, 2020; Badawi et al., 2022). The findings contribute to both academic discourse and managerial practice by offering evidence-based insights into scalable productivity-enhancement strategies for SMEs operating under resource constraints.

2. Literature Review

This study is anchored in a multidisciplinary body of literature encompassing Lean Manufacturing, Six Sigma, Total Productive Maintenance (TPM), Industry 4.0, and energy efficiency management. Together, these paradigms form the theoretical foundation for an integrated operational excellence (OPEX) framework to enhance manufacturing productivity in resource-constrained small- and medium-scale enterprises (SMEs).

2.1. Lean Manufacturing and Waste Elimination

Lean Manufacturing is a systematic approach to maximizing customer value by eliminating non-value-added activities, commonly known as the seven wastes: overproduction, waiting, transportation, excess inventory, motion, overprocessing, and defects. By streamlining process flow and improving workplace organization, Lean enables firms to enhance productivity, reduce costs, and improve delivery performance. Among Lean tools, Value Stream Mapping (VSM) is particularly pivotal, as it provides a holistic visualization of material and information flows across the production system, enabling the identification of bottlenecks, delays, and inefficiencies (Rane et al., 2015).

In the context of Indian manufacturing SMEs, Lean adoption has demonstrated considerable potential despite structural and financial limitations. Empirical studies indicate that VSM-driven interventions lead to significant reductions in lead time, work-in-process inventory, and production waste (Saini & Singh, 2022; Kumar & Shankar, 2022). However, the literature also highlights that Lean implementation in SMEs often requires simplification, employee engagement, and phased deployment to ensure sustainability. These findings underscore the relevance of Lean as a foundational productivity improvement strategy in transformer manufacturing environments characterized by batch production and process variability.

2.2. Six Sigma for Quality Control and Process Stability

While Lean emphasizes flow and waste elimination, Six Sigma focuses on reducing process variation and defects through a structured, data-driven methodology. The Define–Measure–Analyze–Improve–Control (DMAIC) framework provides a systematic roadmap for identifying root causes of quality issues and implementing statistically validated solutions (Antony et al., 2016). Six Sigma has been widely applied in high-volume and quality-critical industries, where defect reduction directly translates into cost savings and customer satisfaction.

Studies in power equipment, cable manufacturing, and related electrical industries demonstrate the applicability of Six Sigma tools, such as cause-and-effect analysis, hypothesis testing, and control charts, to processes similar to transformer manufacturing (Sony, 2019; Dweiri & Ishaq, 2020). For SMEs, Six Sigma helps institutionalize a problem-solving discipline and performance measurement, though challenges related to skill availability and data collection persist. When integrated with Lean principles, Lean Six Sigma (LSS) enables organizations to simultaneously address efficiency and quality dimensions of productivity, making it particularly suitable for complex manufacturing systems.

2.3. Total Productive Maintenance and Equipment Effectiveness

Equipment reliability is a critical determinant of productivity in capital-intensive manufacturing sectors such as transformer production. Total Productive Maintenance (TPM) is an OPEX philosophy that aims to maximize Overall Equipment Effectiveness (OEE) through proactive and preventive maintenance strategies involving operators, maintenance staff, and management. TPM emphasizes autonomous maintenance, planned maintenance, focused improvement, and skill development to reduce breakdowns, minor stoppages, and speed losses (Sharma et al., 2006).

Empirical evidence suggests that TPM implementation in SMEs leads to substantial improvements in equipment availability, performance efficiency, and product quality (Xiang & Chin, 2021). In resource-constrained environments, TPM is particularly effective when integrated with Lean initiatives, as it supports stable process flow and minimizes unplanned downtime. For transformer manufacturing SMEs, where equipment failures can cause significant production delays and rework, TPM is a critical enabler of sustainable productivity improvements.

2.4. Industry 4.0 and Manufacturing Digitalization

Industry 4.0 represents a paradigm shift toward smart manufacturing by integrating digital technologies such as the Internet of Things (IoT), big data analytics, and cyber-physical systems. While large firms often pursue comprehensive digital transformation, SMEs face barriers to it due to costs, technological complexity, and organizational readiness. Recent literature emphasizes that incremental and targeted adoption of Industry 4.0 technologies can yield substantial benefits without requiring extensive capital investment (Chiu et al., 2020).

Low-cost IoT sensors for condition monitoring and predictive maintenance offer a feasible entry point for SMEs, enabling real-time data acquisition and early detection of equipment abnormalities (Badawi et al., 2022). Moreover, data-driven decision-making supported by digital tools enhances transparency in processes, maintenance planning, and continuous improvement initiatives (Helo & Hao, 2022). When aligned with Lean Six Sigma practices, Industry 4.0 technologies serve as enablers, sustaining and amplifying productivity gains by providing timely, accurate, and actionable operational data.

2.5. Energy Efficiency and Energy Cost Deployment

Energy consumption represents a significant cost component in manufacturing operations, particularly in energy-intensive processes such as transformer production. Energy Cost Deployment (ECD) is a Lean-based analytical approach that systematically identifies energy losses across processes and links them to specific improvement opportunities (Braglia et al., 2020). By integrating energy performance into productivity improvement initiatives, ECD enables firms to achieve both economic and environmental benefits.

Studies highlight that structured energy management practices can lead to substantial reductions in energy intensity and operating costs, especially in SMEs where energy inefficiencies often remain hidden (Worrell, 2008). Incorporating ECD into an OPEX framework aligns productivity improvement with sustainability objectives, reinforcing the relevance of energy efficiency as a strategic dimension of manufacturing performance.

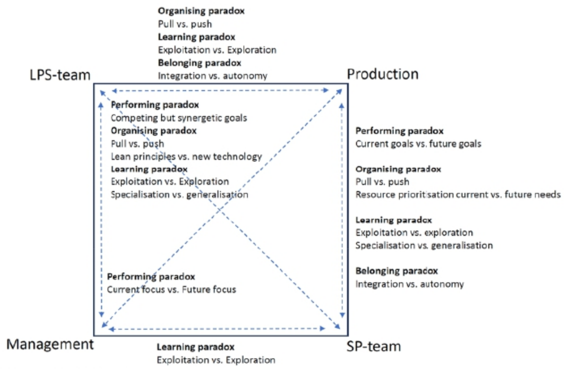

Figure 1. The proposed integrated OPEX framework.
Source: Peter et al. (2024).

The reviewed literature suggests that no single methodology is sufficient to address the multifaceted productivity challenges faced by manufacturing SMEs. Lean Manufacturing provides waste elimination and flow optimization; Six Sigma ensures process stability and quality control; TPM enhances equipment effectiveness; Industry 4.0 enables real-time monitoring and predictive capabilities; and ECD integrates energy efficiency into operational decision-making. While each approach has been studied independently, empirical research on their integrated application, particularly within Indian transformer manufacturing SMEs remains limited.

Accordingly, this study proposes a cohesive, phased OPEX framework that integrates Lean Six Sigma, TPM, Industry 4.0 technologies, and energy efficiency tools in a manner tailored to the SME context. By synthesizing established operational methodologies with emerging digital technologies, the framework aims to deliver sustainable improvements in manufacturing productivity, quality performance, equipment reliability, and energy efficiency.

3. Materials and Methods

This study adopted an in-depth case study approach to examine the application of an integrated Lean Six Sigma and Industry 4.0 framework in a small-scale Indian transformer manufacturing SME, referred to as “ABC Transformers” to preserve confidentiality. The firm employs approximately 150 workers, reports annual turnover below INR 250 crores, and specializes in the production of distribution transformers with a capacity of up to 5 MVA.

Prior to implementation, the company faced persistent operational challenges, including a 55% on-time delivery rate, an 8.5% coil winding defect rate, and frequent machine breakdowns that disrupted production flow. The improvement initiative commenced with a diagnostic phase combining Lean and Six Sigma principles, during which a current-state Value Stream Map (VSM) was developed to visualize material and information flows across the production system.

The VSM revealed an excessive production lead time of 28 days, of which only 18 hours were value-added, with coil winding and oil testing identified as critical bottleneck processes. Concurrently, detailed operational data, including process parameters, defect frequencies, machine downtime records, and energy consumption figures, were systematically collected to establish baseline performance levels. Overall Equipment Effectiveness (OEE) analysis of the coil winding machine indicated a low baseline value of 52%, driven by limited availability (65%), moderate performance efficiency (80%), and quality losses (85%).

In the subsequent analytical phase, root causes of inefficiency and quality variation were identified using a cause-and-effect (fishbone) diagram, which highlighted deficiencies related to manpower skills, inconsistent operating methods, equipment reliability issues, and delayed manual inspection practices. Based on these findings, an integrated set of improvement interventions was implemented. Lean-based layout modifications were introduced to enhance process flow, and a Kanban system was deployed to regulate raw material inventory, particularly copper and core steel.

Six Sigma tools were applied through standardizing operating procedures for coil winding and developing a poka-yoke jig to prevent assembly errors during core installation. To address equipment-related losses, Total Productive Maintenance practices were implemented, including operator-led autonomous maintenance and a structured preventive maintenance schedule. In parallel, selective Industry 4.0 adoption was achieved by installing a low-cost vibration sensor on the winding machine, enabling condition monitoring and predictive maintenance.

An energy-efficiency initiative complemented these efforts, involving a detailed energy audit, replacing inefficient motors with high-efficiency alternatives, and rectifying compressed air leaks. Finally, to ensure the sustainability of performance improvements, control mechanisms such as visual management boards, statistical control charts, and revised training programs were institutionalized, embedding continuous monitoring and standardized work practices into routine operations.

4. Results and Discussion

The key operational performance indicators were systematically measured over a six-month period to evaluate the impact of the integrated Lean Six Sigma and Industry 4.0 implementation, and the comparative outcomes are presented in Table 1

Table 1. Summary of key performance improvement

Performance Metric	Before	After	% Improvement
Production Lead Time (days)	28	20	28.6%
Coil Winding Defect Rate (%)	8.5	3.4	60.0%
On-Time Delivery (%)	55	85	54.5%
OEE - Winding Machine (%)	52	70.2	35.0%
Energy Cost/Unit (₹)	1,250	1,000	20.0%

Table 1 presents the comparative performance of key operational indicators before and after implementing the integrated Lean Six Sigma and Industry 4.0 framework over a six-month period. The results indicate substantial improvements across productivity, quality, delivery reliability, equipment effectiveness, and energy efficiency, demonstrating the comprehensive impact of the phased OPEX intervention.

The production lead time was reduced from 28 days to 20 days, resulting in a 28.6% improvement. This reduction signifies a significant enhancement in process flow following the elimination of non-value-added activities identified through Value Stream Mapping (VSM). The redesign of the production layout and the implementation of a Kanban-based inventory control system improved material movement, reduced waiting time, and enhanced synchronization between upstream and downstream operations. The narrowing of the gap between total lead time and value-added time indicates a shift toward a more efficient and streamlined production system.

The coil winding defect rate decreased markedly from 8.5% to 3.4%, representing a 60.0% improvement. This substantial reduction highlights the effectiveness of Six Sigma interventions, including standardized operating procedures, enhanced operator training, and the introduction of a poka-yoke device for core assembly. By addressing variation in winding tension and improving inspection timeliness, the company achieved greater process stability and higher first-pass yield, thereby reducing rework, material wastage, and associated costs.

On-time delivery performance improved from 55% to 85%, amounting to a 54.5% increase. This improvement reflects the combined effect of shorter lead times, improved equipment reliability, and lower defect rates. The integration of Lean flow optimization with Total Productive Maintenance (TPM) and predictive maintenance significantly reduced unplanned downtime, enabling more accurate production scheduling and reliable order fulfillment. Improved delivery performance enhances customer satisfaction and strengthens competitive positioning in the transformer manufacturing market.

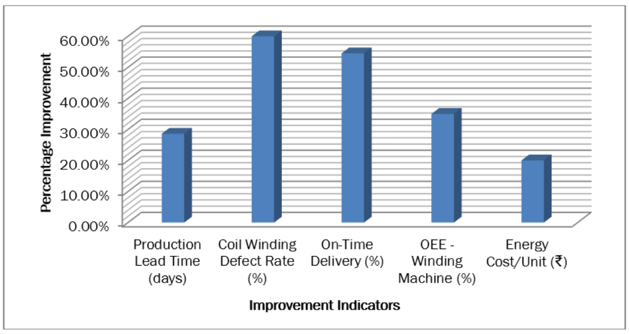

Figure 2. Diagram of Performance Improvement

The Overall Equipment Effectiveness (OEE) of the winding machine increased from 52% to 70.2%, demonstrating a 35.0% improvement. The initial OEE losses were largely attributable to limited availability due to breakdowns and ageing components. Through the implementation of autonomous and preventive maintenance practices, along with the installation of a low-cost vibration sensor for condition monitoring, equipment availability and operational stability improved considerably. Achieving an OEE above 70% represents a meaningful transition toward proactive maintenance management and improved manufacturing discipline.

The energy cost per unit declined from ₹1,250 to ₹1,000, resulting in a 20.0% reduction. This outcome resulted from a structured energy audit, replacement of inefficient motors with high-efficiency alternatives, and correction of compressed air leaks. By incorporating Energy Cost Deployment principles, the firm systematically identified and eliminated energy losses, thereby reducing operational expenses while simultaneously improving environmental sustainability.

The result demonstrates that the integrated OPEX framework generated multidimensional performance improvements rather than isolated gains. The simultaneous enhancement of productivity, quality, delivery reliability, equipment effectiveness, and energy efficiency confirms the synergistic value of combining Lean Six Sigma, TPM, selective Industry 4.0 adoption, and energy management practices within an SME context. The magnitude of these improvements over a relatively short six-month period underscores the practical feasibility and strategic relevance of the proposed framework for transformer manufacturing SMEs in India.

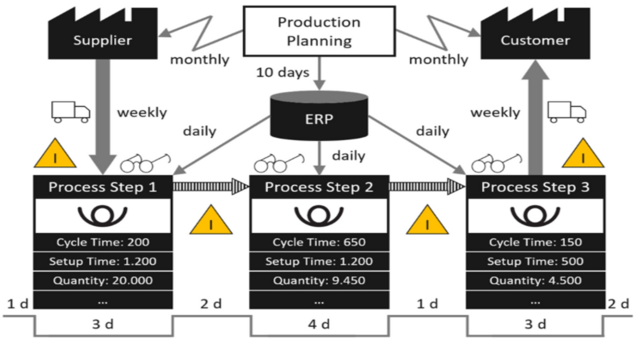

Figure 3. Comparison of the Current-State and Future-State Value Stream Maps (VSM)

Figure 3 illustrates a simplified comparison of the current-state and future-state Value Stream Maps (VSM), highlighting the reduction in total production lead time from 28 days to 20 days following the implementation of the integrated Lean Six Sigma and Industry 4.0 framework. The visual representation captures the flow of materials and information from suppliers to customers through three major process steps, coordinated via production planning and ERP integration. It provides both a macro-level systems perspective and a micro-level view of process performance.

In the current-state configuration (pre-implementation), the value stream revealed significant inefficiencies across the production chain. Although actual cycle times within each process step were relatively short compared to total elapsed time, substantial waiting periods, inventory buffers, and inter-process delays contributed to an overall lead time of 28 days. For instance, Process Step 1, Process Step 2 (coil winding), and Process Step 3 collectively accounted for only a fraction of value-added time, while the remaining duration consisted of queue time, material staging, batch transfers, and scheduling gaps. The coil-winding stage, characterized by high setup time and a high defect rate, emerged as a critical bottleneck. Information flow between production planning, ERP, and shop-floor operations was largely periodic (monthly/weekly), limiting responsiveness and real-time coordination.

The future-state VSM demonstrates a more synchronized and streamlined production system. Through layout redesign, Kanban-based pull control, standardized operating procedures, and improved maintenance practices, non-value-added waiting time between processes was substantially reduced. The implementation of Total Productive Maintenance (TPM) and predictive condition monitoring minimized unplanned downtime, while Six Sigma interventions reduced defect-induced rework loops. Consequently, inter-process delays of 2–3 days were compressed, inventory buffers were lowered, and material flow became more continuous. The cumulative effect of these improvements reduced total lead time by 28.6%, from 28 days to 20 days.

The observed reduction in lead time is consistent with empirical evidence from similar Lean Six Sigma implementations in manufacturing environments, which report significant gains in flow efficiency and defect reduction (Sharma et al., 2022; Dweiri & Ishaq, 2020). The 60% reduction in coil winding defects further reinforces this alignment, as eliminating process variation directly reduces rework cycles and shortens throughput time.

From an equipment performance perspective, Figure 4 indirectly reflects the impact of improved machine reliability on flow stability. The 35% improvement in Overall Equipment Effectiveness (OEE) confirms the role of TPM, combined with active operator involvement, in enhancing the availability, performance, and quality dimensions of equipment utilization (Xiang & Chin, 2021). By stabilizing the bottleneck process, production variability was reduced, enabling smoother downstream operations and improved schedule adherence.

Energy efficiency gains are also embedded within the improved value stream. Reduced waiting time and fewer breakdowns lower idle energy consumption, while targeted actions such as high-efficiency motor installation and compressed air leak rectification contributed to a 20% reduction in energy cost per unit. This outcome validates the effectiveness of integrating lean-energy principles and structured energy audits within operational improvement programs (Braglia et al., 2020).

Importantly, the result also reflects enhanced information flow through ERP-supported daily monitoring and the installation of a low-cost IoT vibration sensor for predictive maintenance. Rather than pursuing full-scale digital transformation, the company adopted a focused digital intervention targeting the primary bottleneck machine. This pragmatic approach exemplifies the “low-cost, high-effect” philosophy for SME digitalization advocated by Panayiotou et al. (2022) and Antony et al. (2022), demonstrating that selective Industry 4.0 integration can amplify Lean Six Sigma benefits without imposing excessive capital burden.

The result visually substantiates the systemic nature of the improvement initiative. The transformation from a push-oriented, delay-prone production system to a more synchronized, pull-driven, and digitally supported value stream illustrates how integrating Lean, Six Sigma, TPM, energy management, and Industry 4.0 tools generates synergistic performance gains. The reduction in lead time from 28 to 20 days serves not only as a quantitative productivity indicator but also as evidence of enhanced operational discipline, process stability, and organizational learning within the SME context.

5. Conclusions

This study set out to examine whether integrating Lean Six Sigma, Total Productive Maintenance (TPM), selective Industry 4.0 technologies, and energy management practices could significantly enhance manufacturing productivity in an Indian transformer manufacturing SME. The central research question guiding the study was whether a phased, resource-sensitive Operational Excellence (OPEX) framework could deliver measurable improvements in productivity, quality, equipment effectiveness, delivery reliability, and energy efficiency within a small-scale enterprise context.

The findings strongly support this proposition. Over a six-month implementation period, the company achieved a 28.6% reduction in production lead time (from 28 to 20 days), a 60% reduction in coil winding defects (from 8.5% to 3.4%), a 54.5% improvement in on-time delivery performance (from 55% to 85%), a 35% increase in Overall Equipment Effectiveness (from 52% to 70.2%), and a 20% reduction in energy cost per unit. These results demonstrate that the integrated framework did not produce isolated improvements but rather generated systemic operational transformation across multiple performance dimensions. Accordingly, the underlying hypothesis that integrating Lean Six Sigma with TPM, energy-efficiency tools, and targeted Industry 4.0 adoption would significantly enhance SME manufacturing performance is empirically supported.

The significance of these findings lies in three major contributions. First, from a theoretical perspective, the study advances the literature by demonstrating the synergistic interaction between traditional OPEX methodologies and emerging digital technologies within an SME environment. While prior studies have examined Lean, Six Sigma, TPM, or Industry 4.0 independently, this research provides empirical evidence that a carefully sequenced integration of these approaches amplifies their collective impact. The case confirms that Industry 4.0 technologies, when applied selectively and strategically, serve as enablers rather than replacements for foundational process improvement methodologies.

Second, from a managerial standpoint, the findings offer a pragmatic roadmap for SMEs operating under financial and technological constraints. The study illustrates that large-scale capital investment is not a prerequisite for digital-enabled productivity gains. Instead, a "low-cost, high-effect" approach, such as deploying a single IoT vibration sensor for predictive maintenance, can significantly enhance equipment reliability and sustain Lean Six Sigma improvements. This insight is particularly relevant for manufacturing SMEs in emerging economies seeking to compete in quality-sensitive and cost-pressured markets.

Third, including energy efficiency within the OPEX framework broadens the definition of productivity to encompass sustainability and cost resilience. The 20% reduction in energy cost per unit highlights the strategic importance of integrating lean-energy principles into operational transformation initiatives. This contributes to the evolving discourse on sustainable manufacturing and Industry 4.0-enabled resource optimization.

The study concludes that integrating Lean Six Sigma with TPM, targeted digitalization, and structured energy management constitutes an effective and scalable pathway for enhancing manufacturing productivity in Indian SMEs. The findings reinforce the argument that operational excellence and digital transformation should not be pursued as parallel initiatives but as mutually reinforcing strategies. Future research may extend this framework across multiple case studies or conduct longitudinal analyses to examine long-term sustainability and scalability across different manufacturing sectors.

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