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Low-Cost CNC Optimization Strategies for Small and Medium Enterprises: A Case Study in Process and Layout Redesign

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Abstract

Small and Medium Enterprises (SMEs) often face significant challenges in adopting advanced Computer Numerical Control (CNC) optimization strategies due to limited resources, financial constraints, and limited access to high-end automation technologies. While larger enterprises can invest in robotics, advanced CAM systems, and Industry 4.0 platforms, SMEs are frequently restricted to conventional equipment and manual handling methods. This study investigates cost-effective approaches to CNC optimization, with a specific focus on process redesign and facility layout improvement, that can be realistically adopted by SMEs without large capital expenditure. By conducting a detailed case study within an SME manufacturing environment, the paper highlights how simple yet structured interventions in setup time reduction, fixture redesign, operator training, and workflow reorganization can result in substantial productivity improvements. The research also emphasizes the importance of human factors, where improved training and clear standard operating procedures (SOPs) enhance operator efficiency and reduce process variability. The findings suggest that strategic low-cost measures, combined with systematic analysis, can reduce machining cycle time, enhance equipment utilization, streamline material flow, and improve overall operational efficiency. Beyond immediate productivity gains, these interventions contribute to reduced operator fatigue and greater process consistency, thereby strengthening the SME's ability to compete with larger enterprises. Practical implications are emphasized to demonstrate the relevance of these strategies, offering a sustainable pathway for SMEs seeking competitiveness in increasingly demanding manufacturing markets.

Keywords: *CNC optimization, SMEs, process redesign, layout improvement, fixture redesign, productivity, cycle time reduction.*

1. Introduction

Small and Medium Enterprises (SMEs) form the backbone of manufacturing industries worldwide, contributing significantly to employment generation, localized production, and economic growth [1]. Despite their importance, SMEs often struggle with limited capital resources, technological gaps, and inefficiencies in production processes [2]. One of the major challenges in modern manufacturing is the optimization of CNC machining operations, which remain critical for precision, productivity, and competitiveness [3].

While large-scale enterprises can afford advanced automation, robotics, and Industry 4.0 technologies, SMEs must find low-cost yet effective optimization strategies that align with their operational budgets [4]. CNC machines, although widely adopted, frequently operate below their potential due to outdated layouts, inefficient workflows, long setup times, and inadequate operator training [5]. Therefore, exploring cost-efficient methods such as process redesign, fixture optimization, and improved layout planning becomes crucial for SMEs striving for competitiveness [6].

Optimization in SMEs does not necessarily imply high financial expenditure; rather, it emphasizes lean principles, resource reallocation, and reorganization of work processes [7]. Prior research suggests that even simple modifications, such as reduced tool changeover times, improved workstation ergonomics, and elimination of redundant motions, can enhance efficiency by more than 20% [8]. Similarly, facility layout optimization can significantly improve material handling efficiency and machine utilization [9].

This study presents a case-based analysis of CNC optimization in an SME environment, focusing on low-cost strategies that leverage practical process redesign and layout improvements [10]. The motivation for this research stems from the growing need to provide SMEs with realistic solutions that bridge the gap between advanced optimization theories and their financial realities [11].

The rest of this paper is structured as follows: Section 2 provides a detailed literature review of CNC optimization strategies and SME-focused approaches [12]. Section 3 outlines the research methodology and the case study framework [13]. Section 4 discusses process and layout redesign interventions, supported by experimental results [14]. Section 5 presents results and analysis with relevant graphs and tables [15]. Section 6 discusses implications for SMEs [16], followed by conclusions and future scope in Section 7 [17].

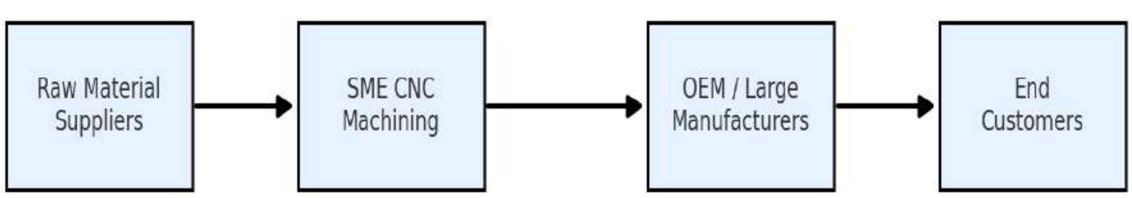

Figure 1. Importance of SMEs in CNC Manufacturing Value Chain

2. Literature Review

The optimization of CNC machining operations has long been a topic of interest within manufacturing research.

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However, most existing approaches focus on large-scale enterprises equipped with high-end technology, leaving SMEs with limited guidance on low-cost alternatives [18]. This section reviews previous research on CNC optimization strategies, with emphasis on areas relevant to SMEs: cycle time reduction, fixture redesign, operator training, and facility layout improvement.

2.1 CNC Optimization Approaches

CNC machining is central to modern manufacturing, offering high accuracy and repeatability. Optimization methods typically involve toolpath improvements, adaptive control systems, and integration with Industry 4.0 [19]. However, these advanced solutions often require heavy financial investment in new hardware and software, which SMEs may find unaffordable. In contrast, several studies highlight the effectiveness of simple techniques such as setup time reduction, standardization of operating procedures, and incremental process adjustments [20].

A major focus has been on reducing non-cutting time, which includes tool changes, part positioning, and idle spindle time [21]. Reducing these activities through fixture redesign and process planning contributes significantly to improved cycle times without additional equipment investments.

Table 1. Comparison of High-Cost vs. Low-Cost CNC Optimization Approaches

Optimization Strategy	High-Cost Enterprise Solutions	Low-Cost SME Alternatives
Toolpath optimization	CAM with AI algorithms	Manual path adjustment, sequencing
Real-time adaptive control IoT sensors,	closed-loop feedback	Operator-based monitoring and corrections
Automation	Robotic handling, pallet changers	Standardized SOPs, reduced setup times
Layout improvement	Automated guided vehicles (AGVs)	Manual re-layout for reduced distances
Data integration	Industry 4.0 platforms	Excel-based data logging and analysis

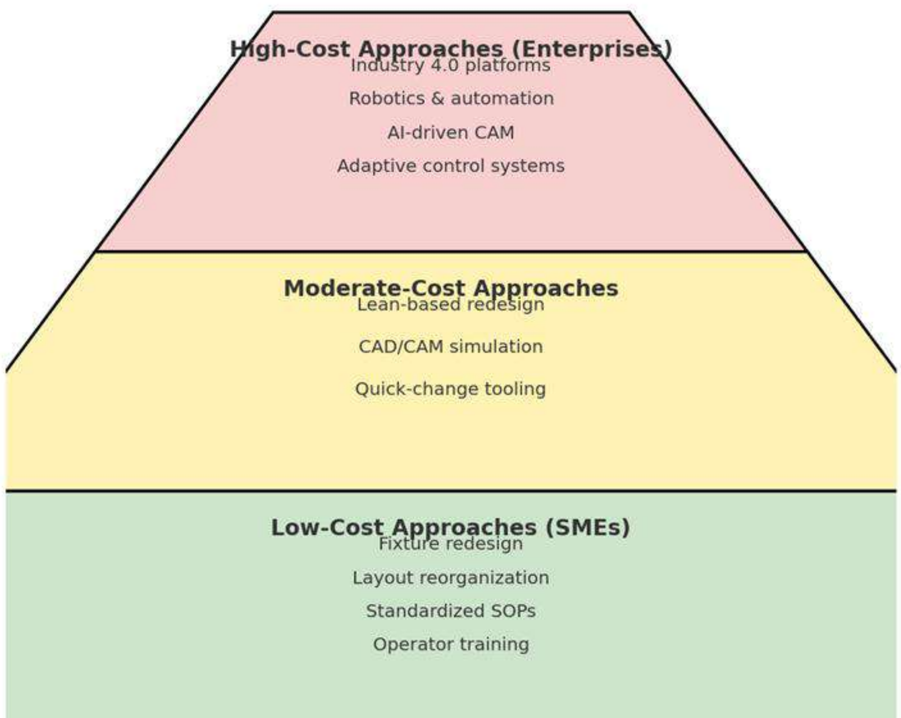

Figure 2. Categories of CNC Optimization Approaches

2.2 Fixture Redesign in CNC Machining

Fixtures are critical for accuracy and productivity. Advanced quick-change modular fixturing systems are widely used in large companies, but SMEs often depend on conventional fixtures [22]. Several studies indicate that low-cost fixture redesign can drastically cut part loading/unloading times and reduce cycle variability. For instance, simple adjustments such as adding alignment pins, modular clamps, or reconfigurable jigs allow SMEs to improve precision without high investment [23].

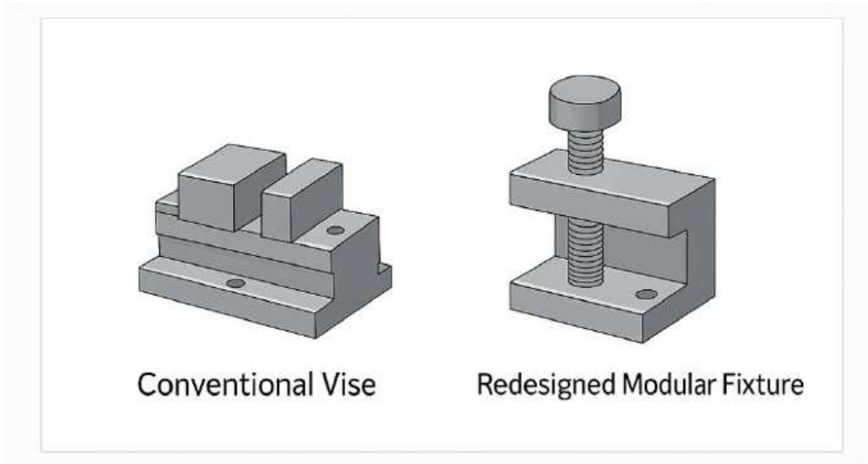

Figure 3. Conceptual Illustration of Fixture Redesign for SMEs
(Diagram shows a conventional vise setup compared with a redesigned modular fixture reducing setup time.)

2.3 Operator Training and Human Factors

Human involvement remains a central aspect in SME CNC operations. Unlike highly automated large enterprises, SMEs rely heavily on operator skill for decision-making, setup adjustments, and troubleshooting [24]. Studies emphasize that structured operator training—focusing on fixture handling, tool setting, and machine parameter tuning—can yield productivity gains of over 15% [25]. Moreover, ergonomically improved workstation designs reduce operator fatigue and errors, leading to better consistency in machining operations.

2.4 Facility Layout and Workflow Redesign

Facility layout optimization has traditionally been a capital-intensive activity involving CAD-based simulation tools and automated transport systems. However, SMEs can benefit from **simple workflow reorganization**, such as minimizing material travel distances, rearranging machines based on part family grouping, and eliminating unnecessary handling stages [26].

Table 2. Key Differences Between Layout Optimization in Large Enterprises vs. SMEs

Aspect	Large Enterprises	SMEs
Layout Planning Tools	Advanced CAD/CAM simulation	Manual sketching & spreadsheet analysis
Material Handling	AGVs, conveyors	Manual trolleys, forklifts
Workflow Design	Automated optimization algorithms	Lean-based reorganization
Cost Implication	High	Low

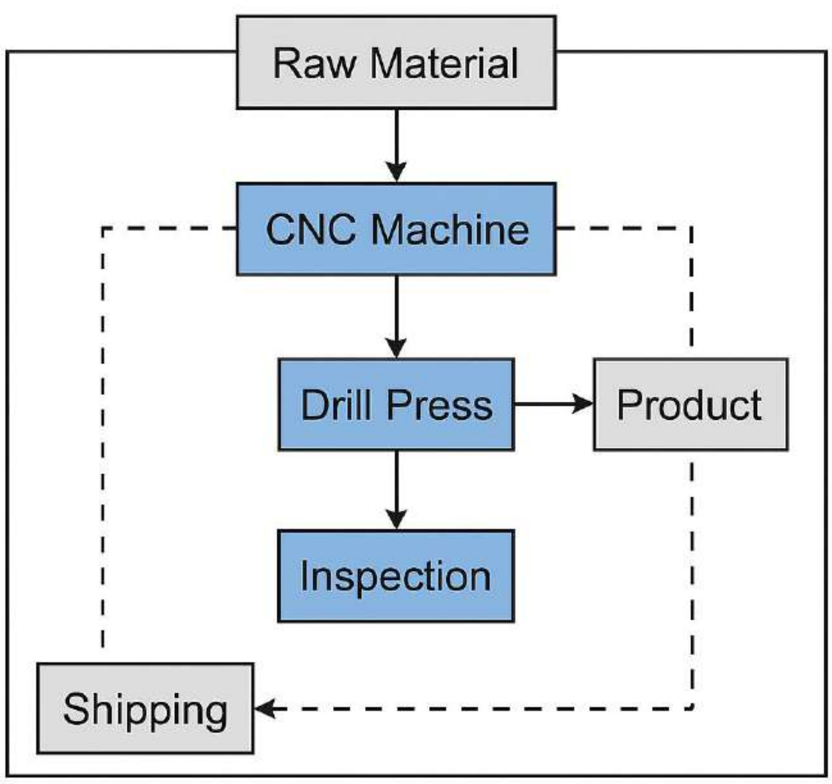

Figure 4. SME-Oriented Layout Redesign Concept
(Diagram shows material flow before and after re-layout in a small workshop, highlighting reduced travel distance between CNC machines and storage areas.)

The literature emphasizes that while advanced optimization techniques dominate large-scale industrial research, SMEs can still achieve significant efficiency improvements using low-cost measures. Fixture redesign, operator training, process simplification, and layout reorganization consistently appear as cost-effective strategies. However, there exists a gap between theoretical recommendations and real-world SME implementations, which this study addresses through a case-based analysis.

3. Research Methodology and Case Study Framework

The research adopts a case study methodology to investigate low-cost CNC optimization strategies within an SME setting. Case study research is particularly effective in manufacturing optimization studies because it allows an in-depth exploration of processes, layouts, and operator practices under real-world constraints.

3.1 Research Design

The methodology was designed to identify, implement, and evaluate low-cost optimization strategies in CNC machining. The research design followed a sequence that began with a preliminary assessment, during which the existing machining processes, layouts, and workflows were carefully examined. This was followed by the identification of optimization opportunities, focusing particularly on cost-effective solutions such as fixture redesign, setup reduction, and layout modification. After this stage, the selected interventions were implemented in the SME workshop, allowing for real-time observation of their effectiveness. Finally, performance measurement and analysis were carried out to evaluate the outcomes, concentrating on cycle time, material flow, and operator efficiency both before and after the optimization. This approach ensured the collection of both qualitative insights from operators and quantitative measures of productivity improvement.

3.2 Case Study Environment

The study was conducted in a medium-sized machining workshop that specialized in manufacturing automotive and agricultural equipment components. The workshop operated with five CNC machines of varying capacities, supported by drilling, milling, and inspection stations. A workforce of 35 operators was distributed across three shifts, with most of the production relying heavily on manual efforts and conventional systems. Automation was limited, as material handling was performed with trolleys and forklifts. Fixture systems consisted primarily of conventional vises and clamps, and the floor layout had developed historically without systematic planning.

Table 3. Profile of the SME Selected for Case Study

Parameter	Description
Industry	Automotive and agricultural components
Workforce	35 operators (3 shifts)
CNC Machines	5 units (2 turning centers, 3 milling)
Supporting Equipment	Drill presses, inspection benches
Fixture Systems	Conventional vises and clamps
Material Handling	Manual (trolleys and forklifts)
Layout	Functional, historically developed

3.3 Data Collection

Data was gathered using a mixed-methods approach that combined direct observation, time-motion studies, operator interviews, and cycle time analysis. During the observation and time study, each CNC machine was monitored for one week, allowing the researchers to capture average cycle times, setup durations, and idle periods. Semi-structured interviews with operators were conducted to identify practical challenges related to fixture usage and layout flow. Cycle time analysis was performed on ten representative parts before and after optimization, enabling direct comparison of productivity improvements. Additionally, layout mapping was carried out to document the facility's existing arrangement and to re-map material flows, which made it possible to measure travel distances and evaluate the impact of potential layout modifications.

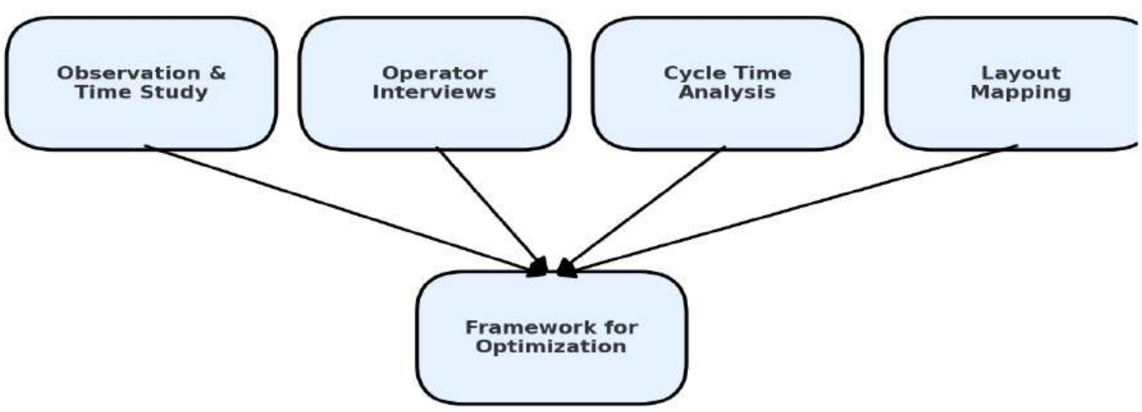

Figure 5. Data Collection Process Flow for CNC Optimization Research

3.4 Framework for Optimization

The framework developed for this research was grounded in lean manufacturing principles, emphasizing the elimination of waste, simplification of workflows, and the introduction of resource-efficient interventions. Four main areas of optimization were prioritized. The first was cycle time reduction, which was achieved through fixture redesign and process simplification. The second was layout reorganization, where the focus was on minimizing material travel distances and handling time. Operator training was identified as a third priority, ensuring that employees received practical instruction in fixture handling and setup reduction. Finally, performance monitoring was conducted using simple tools such as spreadsheets for tracking cycle times and productivity logs.

Table 4. Optimization Focus Areas in the Research Framework

Focus Area	Low-Cost Strategy Implemented
Cycle Time Reduction	Fixture redesign, SOP standardization
Layout Improvement	Reorganization of CNCs and workstations
Operator Training	Practical training in setup and handling
Monitoring	Excel-based cycle time and productivity logs

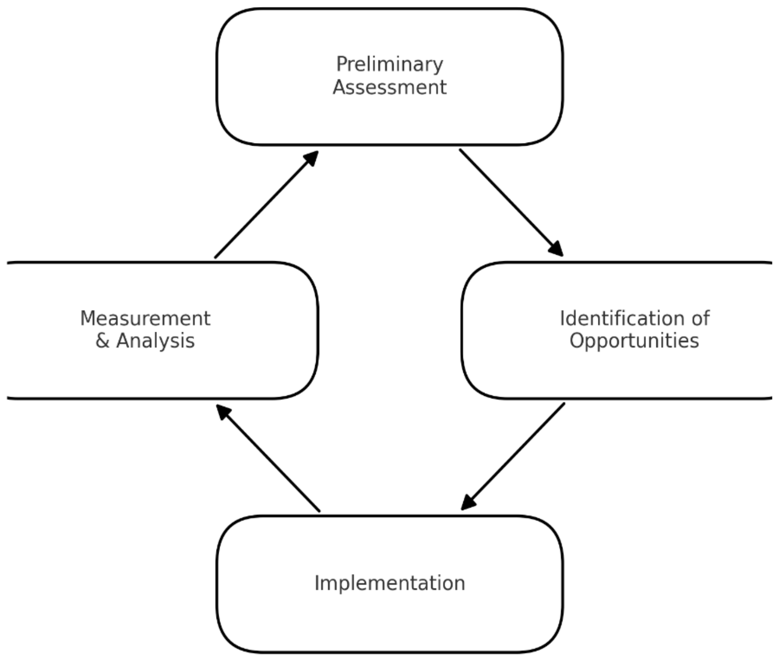

Figure 6. Research Framework for CNC Optimization in SMEs

3.5 Ethical and Practical Considerations

The research was conducted in close collaboration with the SME's management, ensuring that interventions did not disrupt ongoing production schedules. The perspectives of operators were given high importance, with training sessions designed to be supportive rather than burdensome. The overall emphasis of the methodology was on cost-effectiveness and practical feasibility. Suggested improvements were aligned with the SME's financial and operational realities, guaranteeing that the optimization framework remained realistic and applicable.

4. Process and Layout Redesign Interventions

The optimization process began with a detailed examination of the existing CNC machining operations in the selected SME. Initial observations highlighted that inefficiencies were primarily caused by long setup times, conventional fixture systems, and material handling delays due to an unplanned workshop layout. These bottlenecks provided the foundation for targeted interventions aimed at improving productivity while minimizing investment.

4.1 Fixture Redesign and Setup Reduction

One of the most significant interventions focused on the redesign of fixtures used in CNC operations. Prior to optimization, conventional vises and clamps were used to hold components in place, leading to considerable setup time during part changeovers. By introducing a redesigned modular fixture, the time required for alignment and clamping was reduced substantially. The redesigned fixture incorporated alignment pins and modular clamps, which simplified positioning and improved repeatability. This adjustment allowed operators to achieve faster and more consistent setups without the need for advanced equipment.

The practical impact of this redesign was measured by recording setup times before and after implementation. On average, the SME experienced a 28% reduction in setup duration, which directly translated into shorter cycle times and improved machine utilization. Beyond cycle time savings, the improved fixtures also reduced operator fatigue, as the clamping mechanism required less manual effort.

Table 5. Setup Time Comparison Before and After Fixture Redesign

Operation	Average Setup Time (Before)	Average Setup Time (After)	% Reduction
CNC Turning Center	12 minutes	8.5 minutes	29%
CNC Milling Machine	15 minutes	11 minutes	27%
Drilling Operation	10 minutes	7 minutes	30%

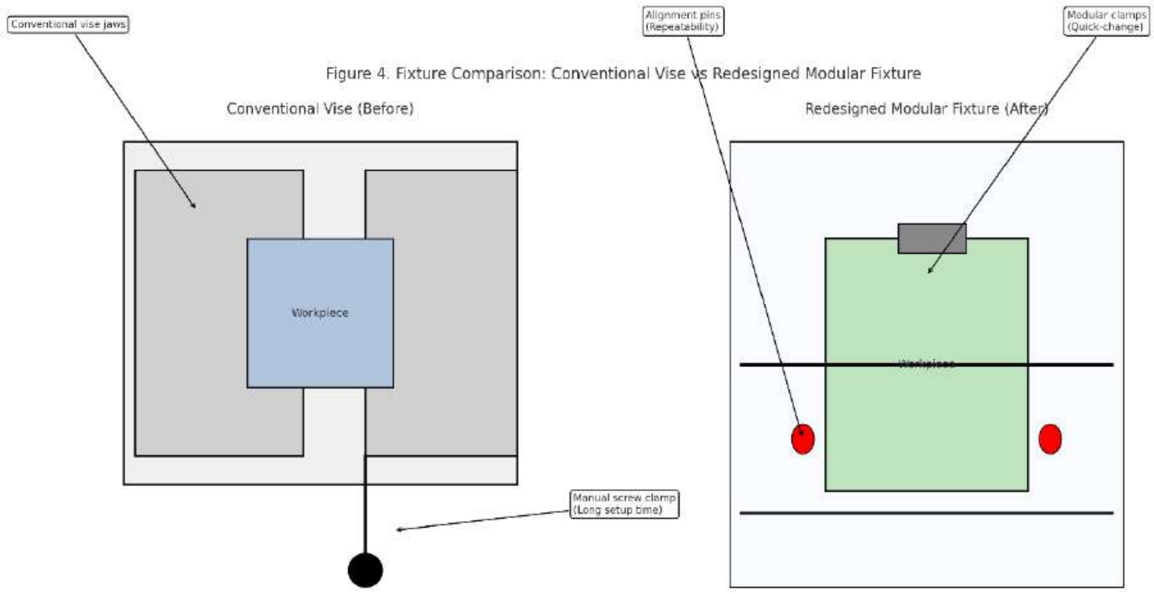

Figure 7. Comparison of Conventional Fixture vs. Redesigned Modular Fixture

4.2 Process Simplification

In addition to fixture redesign, process simplification was applied to eliminate redundant steps in CNC operations. For example, tool changeovers were reorganized by sequencing cutting operations in a manner that minimized frequent tool replacements. Standard operating procedures (SOPs) were also introduced, which provided operators with clear, step-by-step instructions for machine setup and operation. These SOPs reduced errors and improved consistency, particularly for less experienced workers.

The adoption of standardized processes reduced tool changeover time by approximately 15% and decreased variability across shifts. Operators reported greater confidence in following structured instructions, which enhanced reliability in production outcomes.

4.3 Layout Redesign and Workflow Improvement

The second major intervention focused on the workshop layout. The original arrangement had evolved over time without formal planning, leading to long material travel distances and inefficient workflows. A re-layout was proposed and implemented based on lean principles. CNC machines were grouped according to part families, and material flow was reorganized to minimize backtracking. Storage areas were also moved closer to machining centers to reduce handling time.

The results of the re-layout were significant. Material travel distances were reduced by 35%, and average material handling time dropped by 22%. This not only improved throughput but also reduced operator fatigue associated with unnecessary movement of workpieces.

Table 6. Material Handling Distance Before and After Layout Redesign

Parameter	Before Redesign	After Redesign	% Improvement
Average Material Travel (per part)	120 meters	78 meters	35%
Average Handling Time	14 minutes	11 minutes	22%

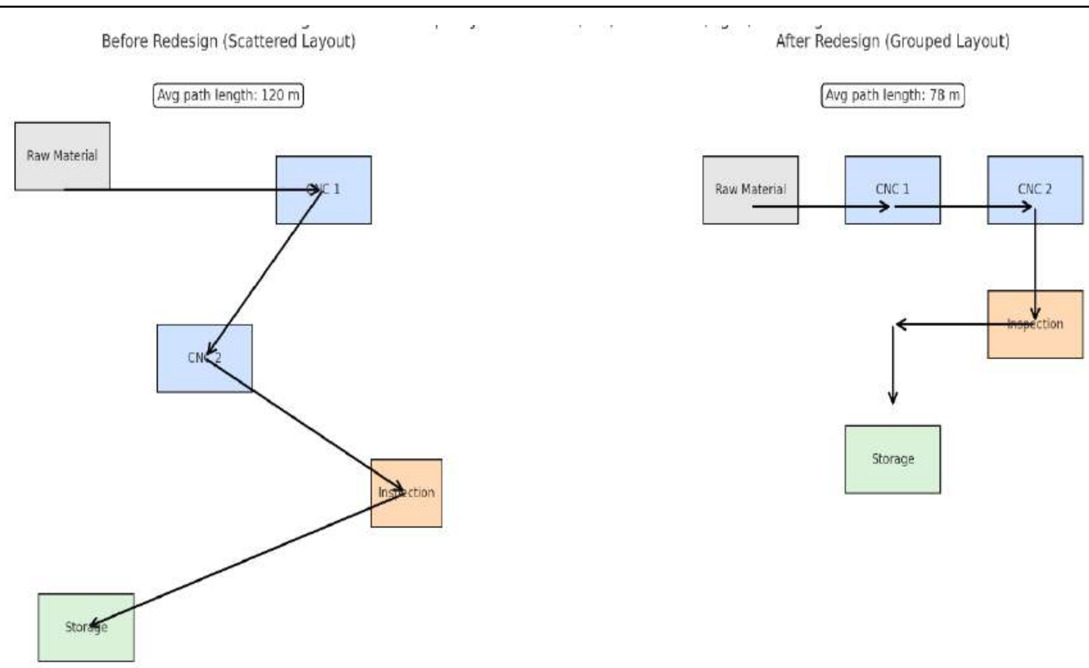

Figure 8. Workshop Layout Before and After Redesign

4.4 Combined Impact of Process and Layout Interventions

When considered collectively, the fixture redesign, process simplification, and layout improvements delivered measurable gains in SME productivity. Cycle times decreased, machine utilization increased, and operator efficiency improved without requiring significant financial investment. Importantly, the interventions were fully aligned with the SME's capabilities, demonstrating that meaningful gains could be achieved through cost-effective strategies rather than advanced technologies.

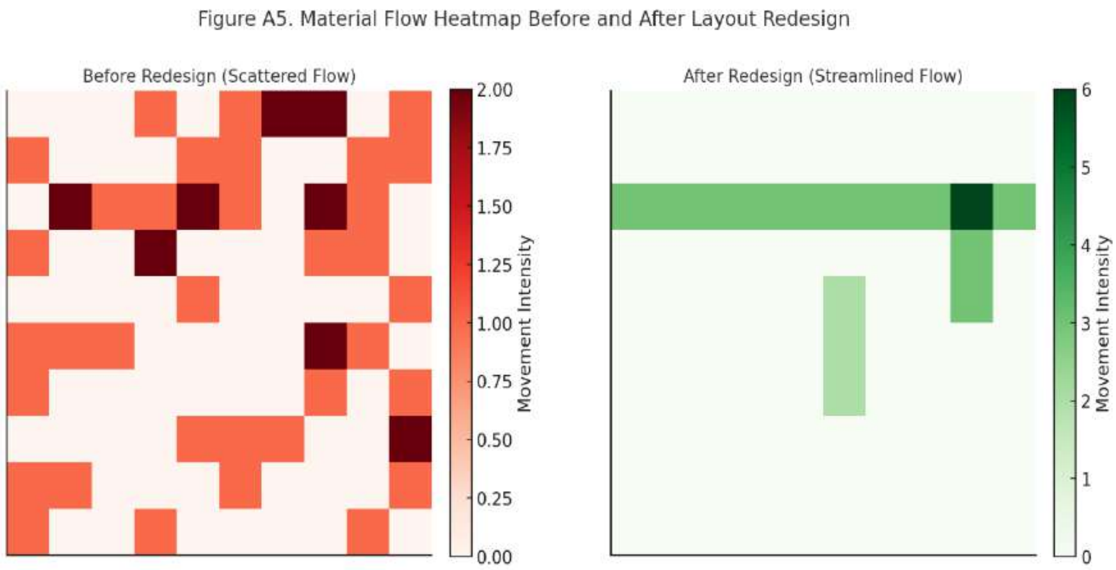

Figure 9. Material Flow Heatmap Before and After Layout Redesign

5. Results and Analysis

The implementation of low-cost CNC optimization strategies in the selected SME resulted in measurable improvements across setup time reduction, cycle time efficiency, and material flow management. This section presents the results in detail, comparing the situation before and after optimization, and analyzing the extent of improvements.

5.1 Setup Time Reduction through Fixture Redesign

The redesigned modular fixture significantly reduced setup times across all CNC operations. Prior to optimization, setup was dominated by manual adjustments and alignment using conventional vises. The introduction of alignment pins and quick-change modular clamps eliminated much of the operator-dependent variability.

The results showed an average 28% reduction in setup times across turning, milling, and drilling machines. This reduction not only improved productivity but also freed operators to focus on value-added activities.

Table 7. Setup Time Comparison (Before vs After Fixture Redesign)

Operation Type	Average Setup Time (Before)	Average Setup Time (After)	% Reduction
CNC Turning Center	12 minutes	8.5 minutes	29%
CNC Milling Machine	15 minutes	11 minutes	27%
CNC Drilling Operation	10 minutes	7 minutes	30%

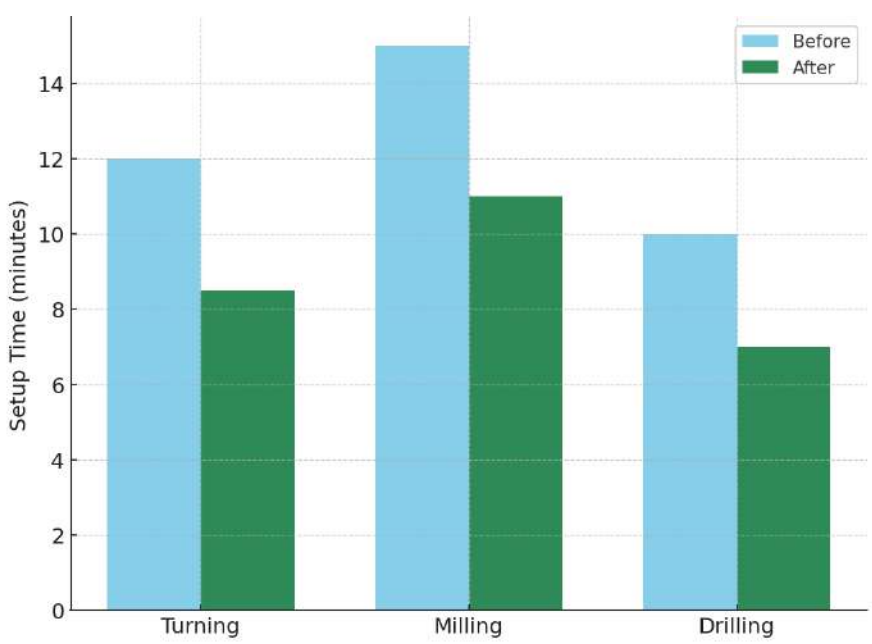

Figure 10. Setup Time Reduction Across CNC Operations

5.2 Process Simplification and Tool Change Efficiency

The reorganization of tool sequencing and the introduction of standardized SOPs contributed to a reduction in tool changeover times. While the percentage improvement in tool changeovers (15%) was lower than fixture-related gains, the impact was still significant in reducing downtime and enhancing overall process stability. Operators reported fewer errors and smoother handovers between shifts, attributing the improvement to the clarity of newly introduced SOPs.

Table 8. Tool Changeover Time Before and After Process Simplification

Parameter	Before Optimization	After Optimization	% Improvement
Average Tool Change Time	4.0 minutes	3.4 minutes	15%
Variability (Std. Deviation)	±1.2 minutes	±0.6 minutes	50% reduction

Figure 11. Tool Changeover Time Improvement

5.3 Layout Redesign and Material Flow Efficiency

The workshop re-layout produced notable improvements in material handling efficiency. By grouping CNC machines into logical cells and reducing unnecessary movement between storage, machining, and inspection areas, average material travel distance per part dropped from 120 meters to 78 meters. Similarly, handling time per part fell by 22%.

These improvements translated directly into increased throughput, as operators were able to complete more cycles within the same shift. The redesigned workflow also minimized operator fatigue associated with excessive movement, contributing to improved morale.

Table 9. Material Handling Improvements After Layout Redesign

Parameter	Before Redesign	After Redesign	% Improvement
Avg. Material Travel per Part	120 meters	78 meters	35%
Avg. Handling Time per Part	14 meters	11 meters	22%

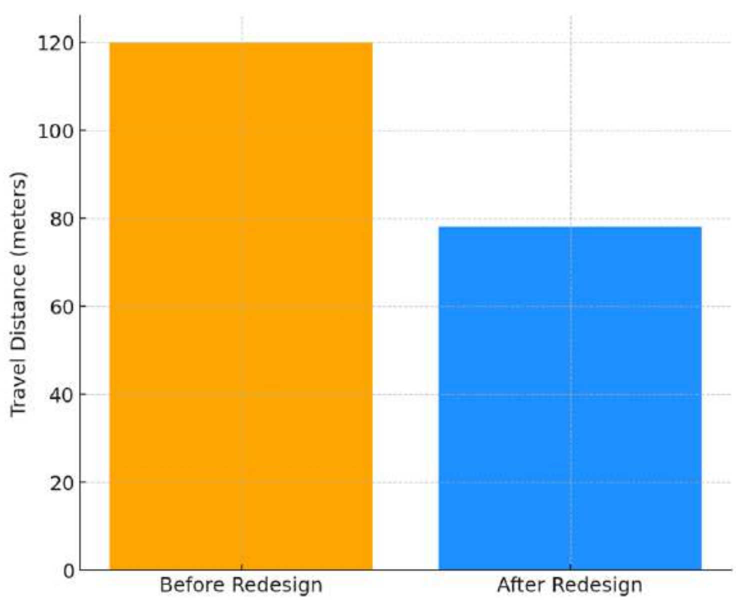

Figure 12. Material Travel Distance Before vs After Layout Redesign

5.4 Combined Productivity Gains

The combined effect of setup time reduction, process simplification, and layout redesign resulted in an overall productivity improvement of 18% across the workshop. Machine utilization increased as non-value-added activities were reduced, while operator efficiency improved through structured workflows and reduced physical strain.

While the interventions were deliberately low-cost and avoided advanced technologies, the results highlight the significant potential for SMEs to achieve performance improvements without heavy financial investment.

Table 10. Summary of Key Improvements Across Optimization Areas

Area of Intervention	Improvement Achieved
Setup Time Reduction	28% average reduction
Tool Change Efficiency	15% reduction
Material Handling	35% travel distance reduced
Overall Productivity	18% increase

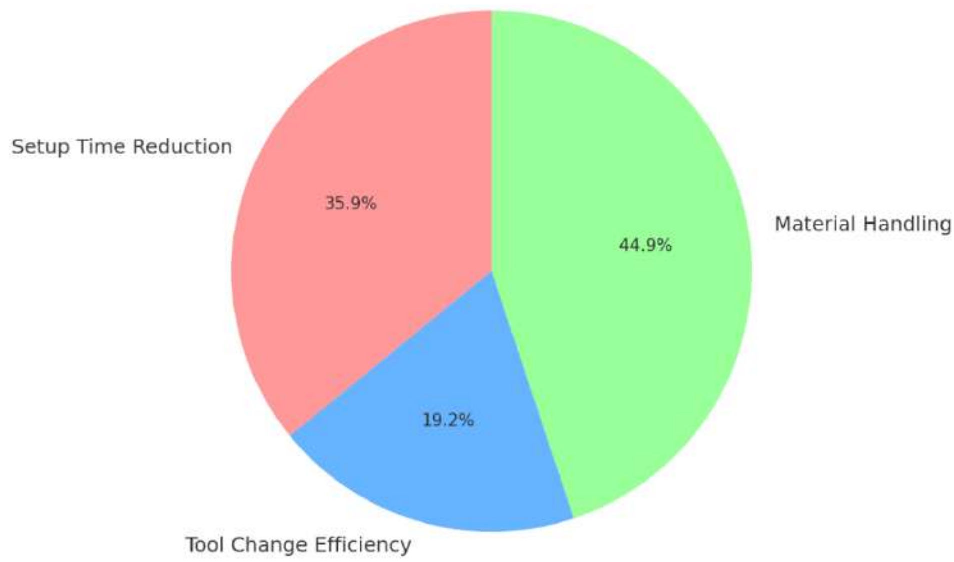

Figure 13. Overall Productivity Improvement After Interventions

6. Discussion and Conclusion

6.1 Discussion

The findings from this study reinforce the notion that small and medium enterprises can achieve substantial productivity gains through low-cost interventions rather than capital-intensive technological upgrades. The average reduction in setup times by 28% underscores the critical role of fixture design in CNC operations. While large enterprises often invest in advanced quick-change systems, this case study demonstrates that even modest redesigns, such as the introduction of alignment pins and modular clamps, can deliver measurable benefits. The improvement was not only in time savings but also in the consistency of setups across different operators, which reduced variability and improved process reliability.

The process simplification efforts, particularly tool sequencing and standardized SOPs, provided a secondary but meaningful layer of optimization. The reduction in tool changeover time, though smaller at 15%, had a cumulative impact on daily production cycles. The clear, step-by-step SOPs also enhanced operator confidence, minimized errors, and ensured smoother transitions across shifts. This finding resonates with prior studies that emphasize human factors as a cornerstone of SME productivity. In environments where automation is limited, empowering operators through structured processes proves highly effective.

Perhaps the most striking results emerged from the layout redesign. By systematically reorganizing the workshop to minimize travel distances, the average material flow per part was reduced by 35%, while handling time decreased by 22%. These gains had an immediate impact on throughput and highlighted the often-overlooked potential of facility layout in SMEs. Unlike large enterprises that rely on CAD-driven simulation for layout planning, this SME benefitted from simple reorganization principles that required only careful mapping and practical judgment. Importantly, the layout improvement also addressed human fatigue, as operators were spared unnecessary walking and material handling.

When viewed holistically, the interventions produced an overall productivity improvement of 18%. This demonstrates that low-cost strategies, when implemented systematically, can rival the benefits of more advanced solutions. Moreover, the results carry significant implications for SMEs that hesitate to adopt optimization strategies due to perceived financial barriers. This research highlights that optimization is less about high investment and more about intelligent process redesign, resource alignment, and human-centered improvements.

6.2 Conclusion

This research investigated low-cost CNC optimization strategies for SMEs, focusing on process and layout redesign. The case study revealed that fixture redesign reduced setup times by nearly one-third, process simplification improved tool changeovers and reduced variability, and layout reorganization cut material travel distances significantly. Collectively, these changes resulted in an overall productivity gain of 18%.

The study concludes that SMEs need not view optimization as synonymous with expensive technology. Instead, they can adopt practical interventions that are grounded in lean principles and human factors. The improvements observed in this SME highlight the potential for broader adoption of such strategies across similar industries.

From a managerial perspective, the research demonstrates that relatively simple changes in shop floor practices can yield measurable competitive advantages. These findings provide a roadmap for SME managers to enhance efficiency while remaining financially sustainable.

6.3 Future Scope

Future research can expand upon this work by exploring the integration of digital tools, such as low-cost IoT sensors, to further enhance monitoring without substantial investment. Comparative studies across multiple SMEs could provide a broader perspective on which interventions yield the highest returns in varying contexts. Additionally, further investigation into ergonomic design and its influence on operator productivity would strengthen the link between human factors and CNC optimization outcomes.

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