

An Integrated Lean Six Sigma Framework for Waste Reduction and Resource Efficiency in Manufacturing

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Abstract

Manufacturing industries face increasing challenges related to material waste, inefficient resource utilization, process variability, and rising operating costs. This study develops an integrated Lean Six Sigma framework for reducing waste and improving resource efficiency in manufacturing by combining Lean Manufacturing, Six Sigma, and data-driven process improvement techniques. The framework incorporates DMAIC, value stream mapping, 5S, Statistical Process Control (SPC), Pareto analysis, Failure Mode and Effects Analysis (FMEA), and root cause analysis. The reported evaluation indicates that defects decreased from 12% to 4.5%, cycle time decreased from 120 to 85 minutes, and process capability (Cpk) improved from 0.95 to 1.45. Estimated annual cost savings were approximately US\$18,500, while customer satisfaction increased by 18%. These findings indicate that an integrated Lean Six Sigma approach can provide a structured basis for waste reduction, improved process performance, and more efficient resource utilization. The framework supports continuous improvement through systematic process analysis, data-driven decision-making, and performance monitoring.

Keywords: Lean Manufacturing; Six Sigma; Resource Efficiency; Waste Reduction; Process Optimization; DMAIC; Sustainable Manufacturing; Continuous Improvement.

1. Introduction

Manufacturing industries face increasing challenges related to material waste, inefficient resource utilization, process variability, quality problems, and rising operating costs. These challenges create a need for systematic approaches that can improve manufacturing efficiency while reducing non-value-added activities and unnecessary consumption of resources. Lean Manufacturing provides a structured approach for identifying and reducing waste within production processes and has been applied across different manufacturing environments to improve process performance and resource utilization [1–3].

Six Sigma complements Lean Manufacturing by providing a systematic and data-driven approach to reducing process variation and defects. The DMAIC (Define, Measure, Analyze, Improve, Control) methodology provides a structured sequence for defining process

problems, measuring current performance, identifying root causes, implementing improvements, and maintaining process gains. The combination of Lean and Six Sigma therefore enables organizations to address both non-value-added activities and process variation within an integrated improvement framework [4,5].

Lean Manufacturing research has identified several established practices for improving production flow and reducing waste, including value stream mapping, Just-in-Time (JIT), Kaizen, process standardization, and continuous improvement [6–8]. These approaches can support improvements in material flow, production efficiency, inventory management, and process performance. However, the effectiveness of Lean Six Sigma implementation depends on appropriate selection and application of improvement tools as well as organizational factors such as management commitment, employee involvement, training, and strategic alignment [9,10].

The increasing emphasis on sustainable manufacturing has further expanded the application of Lean Six Sigma. Sustainable Lean approaches seek to connect operational efficiency and waste reduction with improved resource utilization and environmental performance [11]. Knowledge-based and data-supported approaches have also been investigated for improving the resource efficiency of manufacturing systems, demonstrating the potential of combining process-improvement methods with information-based decision-making [12].

Manufacturing systems are also undergoing significant technological changes through the adoption of Industry 4.0 technologies. The increasing use of automation, interconnected systems, data analytics, and cyber-physical technologies provides opportunities for real-time monitoring and data-driven process improvement. Recent work published in IRJIST has examined a hybrid framework for risk assessment in automated manufacturing systems, combining conventional engineering approaches with machine-learning and digital-twin-based techniques [13]. Such developments highlight the growing importance of structured analytical frameworks for managing and improving increasingly complex manufacturing environments.

Despite the established application of Lean Six Sigma, several challenges remain. Existing research has extensively examined successful implementations, while comparatively less attention has been given to the long-term sustainability of improvements, implementation difficulties, and the conditions required to maintain process gains over time [9,14]. Furthermore, manufacturing organizations differ in their processes, available resources, workforce capabilities, technological infrastructure, and operational requirements. Therefore, an improvement framework needs to be sufficiently structured to support systematic analysis while remaining adaptable to different manufacturing environments.

Against this background, the present study develops an integrated Lean Six Sigma framework for reducing waste and improving resource efficiency in manufacturing. The framework combines Lean Manufacturing and Six Sigma principles with data-driven process-improvement techniques. It incorporates tools including DMAIC, value stream mapping, 5S, Statistical Process Control (SPC), Pareto analysis, Failure Mode and Effects Analysis (FMEA), and root cause analysis to identify

inefficiencies, examine their underlying causes, implement targeted improvements, and monitor process performance.

The study further evaluates the framework using manufacturing performance indicators related to defects, cycle time, cost efficiency, customer satisfaction, process capability, and employee engagement. The overall objective is to provide a systematic and practical approach for identifying manufacturing waste, improving resource utilization, and supporting continuous process improvement.

2. Literature Review

2.1. Lean Six Sigma in Manufacturing

Lean Six Sigma (LSS) integrates Lean Manufacturing and Six Sigma methodologies to address waste, process variation, quality, and operational efficiency. Lean Manufacturing emphasizes the identification and elimination of non-value-added activities, whereas Six Sigma focuses on reducing process variation and defects through structured and data-driven improvement methods [4,5,20]. The combined approach has therefore developed into a widely studied framework for manufacturing process improvement [5,16,20].

Literature reviews have demonstrated the application of Lean and Six Sigma across a range of manufacturing environments. Lean Manufacturing research has particularly focused on waste reduction, process flow, inventory, production efficiency, and continuous improvement [6]. Studies of manufacturing applications have also demonstrated the use of Lean principles for reducing waste and improving production processes in specific industrial settings [1,3].

2.2. Lean Manufacturing Tools and Process Improvement

Several Lean tools are commonly used to identify and reduce inefficiencies within manufacturing processes. Value stream mapping provides a means of examining material and information flows, while Just-in-Time and pull-based approaches seek to align production activities with demand. Kaizen emphasizes continuous incremental improvement, while standardized processes and error-proofing techniques can support consistent process performance [7,8]. These Lean practices can be complemented by Six Sigma's DMAIC methodology. Through the Define, Measure, Analyze, Improve, and Control

phases, DMAIC provides a structured approach for investigating process problems and evaluating improvement measures. The use of statistical analysis and process-performance measurements allows improvement activities to be based on measurable evidence rather than observation alone [4,15].

2.3. Critical Success Factors for Lean Six Sigma

Although Lean Six Sigma provides established improvement tools, successful implementation also depends on organizational conditions. Previous studies have identified factors including management commitment, employee involvement, training, organizational culture, communication, and alignment between improvement projects and organizational objectives as important considerations in LSS implementation [9,10].

These factors can be particularly significant for small and medium-sized enterprises (SMEs), where limitations in financial resources, workforce capabilities, technical expertise, and organizational infrastructure may affect implementation. A systematic review of LSS in SMEs highlighted the need to consider the specific characteristics and constraints of smaller manufacturing organizations when applying improvement frameworks [17].

2.4. Empirical Applications and Resource Efficiency

Empirical studies have examined Lean Six Sigma using case studies, statistical analysis, surveys, and other quantitative approaches. Manufacturing applications have reported improvements in areas such as process efficiency, defect reduction, cycle time, and resource utilization [1,12,18]. Six Sigma case studies have similarly demonstrated the application of structured quality-improvement methods to manufacturing processes [19,20].

Resource efficiency has become an increasingly important dimension of manufacturing improvement. Knowledge-based approaches have been investigated for improving the efficiency of manufacturing systems, while sustainable Lean research has examined the relationship between Lean practices and organizational performance [11,12]. These studies indicate that manufacturing improvement can extend beyond conventional productivity measures to include more efficient utilization of materials and other resources.

2.5. Lean Six Sigma and Industry 4.0

The development of Industry 4.0 has created new opportunities for integrating Lean Six Sigma with digital manufacturing technologies. Technologies such as the Internet of Things, data analytics, cyber-physical systems, machine learning, and digital technologies can support real-time process monitoring and data-driven decision-making.

Research has examined the integration of Lean Six Sigma with advanced manufacturing technologies, including applications within automotive-component manufacturing [18]. In addition, recent IRJIST research has proposed a hybrid risk-assessment framework for automated manufacturing systems that combines conventional engineering techniques with machine-learning and digital-twin approaches [13]. Such developments demonstrate the increasing relevance of data-driven approaches within modern manufacturing environments.

2.6. Sustainability and Green Lean Manufacturing

The relationship between Lean Manufacturing and sustainability has also received increasing research attention. Sustainable Lean approaches seek to combine waste reduction and process efficiency with broader environmental and resource-efficiency objectives [11]. The integration of Lean principles with sustainability therefore extends the traditional focus on productivity and quality toward more efficient utilization of manufacturing resources.

However, sustainability-oriented improvement requires continued monitoring because short-term improvements may not necessarily be maintained over longer periods. This creates a need for frameworks that incorporate control mechanisms and continuous improvement rather than focusing only on immediate process gains.

2.7. Research Gaps

Although the literature demonstrates substantial evidence supporting Lean Six Sigma for manufacturing improvement, several gaps remain. First, many studies focus on individual case studies or specific Lean and Six Sigma tools, which can make it difficult to establish a broadly applicable framework for different manufacturing conditions [5,14]. Second, although successful implementations are

frequently reported, comparatively less attention has been given to unsuccessful projects, implementation barriers, and the organizational factors that prevent improvement initiatives from being sustained [9,14].

Third, the increasing integration of manufacturing with digital technologies creates a need to connect conventional Lean Six Sigma practices with data-driven monitoring and analysis. Modern manufacturing systems generate increasing amounts of operational information, but the effective use of such information requires appropriate measurement, analytical methods, and continuous-control mechanisms [13,18].

Finally, the long-term sustainability of Lean Six Sigma improvements remains an important area for further investigation. Maintaining improvements requires continuous monitoring, employee participation, appropriate performance indicators, and organizational support. Addressing these issues can strengthen the practical applicability of Lean Six Sigma for resource-efficient manufacturing.

2.8. Positioning of the Present Study

Based on the identified literature, the present study focuses on developing an integrated framework that combines Lean Manufacturing and Six Sigma tools for waste reduction and resource-efficiency improvement. Rather than focusing on a single improvement technique, the proposed framework connects waste identification, value-stream analysis, quantitative measurement, root-cause investigation, targeted improvement, and process control.

The framework therefore builds on established Lean Six Sigma principles while incorporating data-driven evaluation and continuous monitoring. Its objective is to provide a structured approach that can be applied to manufacturing processes to identify inefficiencies, improve resource utilization, and support sustained process improvement.

3. Methodology

3.1. Approach

The study applies a systematic approach that integrates Six Sigma and Lean Manufacturing principles to improve resource utilization and reduce waste in manufacturing processes. Six Sigma provides a data-driven approach for

reducing process variation and defects, thereby improving consistency and quality, while Lean Manufacturing focuses on eliminating non-value-added activities, simplifying operations, and improving productivity. The integration of these approaches enables the identification of process inefficiencies, analysis of their underlying causes, and implementation of targeted improvement measures.

The proposed approach uses process data and systematic analysis to support decision-making and evaluate manufacturing performance. The methodology incorporates waste identification, value stream mapping, process standardization, continuous improvement, error-proofing, root cause analysis, and performance monitoring. Employee development and automation are also considered where appropriate to improve resource utilization and sustain process improvements. The integration of Lean Manufacturing and Six Sigma principles is illustrated in Figure 1.

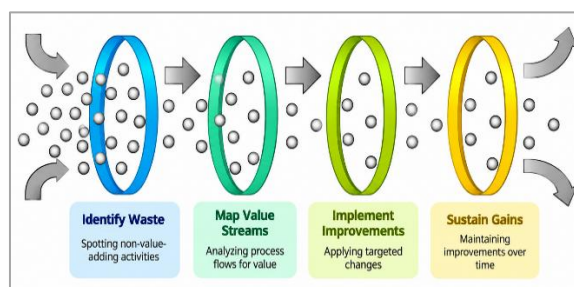


Figure 1. Integrating Six Sigma and Lean for efficiency.

The study adopts the DMAIC (Define, Measure, Analyze, Improve, Control) methodology for improving existing processes and considers DMADV (Define, Measure, Analyze, Design, Verify) where a new process or design is required. The DMAIC framework provides a structured sequence for identifying problems, establishing baseline performance, determining root causes, implementing improvements, and maintaining the achieved gains.

In the Define phase, the problem is identified using available historical information and stakeholder inputs. The project objectives, customer requirements, scope, and process boundaries are established using tools such as the project charter and SIPOC (Suppliers, Inputs, Process, Outputs, Customers) framework. In the Measure phase, critical process variables and performance indicators are identified, followed by the development of a data-collection plan. Baseline process performance is established using appropriate and validated measurement procedures.

In the Analyze phase, potential root causes of identified inefficiencies are examined using statistical analysis, process mapping, Fishbone diagrams, and other appropriate analytical techniques. Where applicable, hypothesis testing may be used to examine relationships between process variables and observed performance.

In the Improve phase, potential improvement measures are identified and evaluated. Cost-benefit analysis and Failure Mode and Effects Analysis (FMEA) are used to assess possible improvement alternatives, and suitable solutions may be evaluated through pilot implementation before wider application.

In the Control phase, mechanisms are established to maintain the improvements achieved during the preceding stages. These include updating standard operating procedures, applying control charts, training relevant personnel, and establishing monitoring and control plans. Continuous monitoring is used to identify deviations and support sustained process performance. The overall Lean Six Sigma improvement framework is further illustrated in Figure 2.

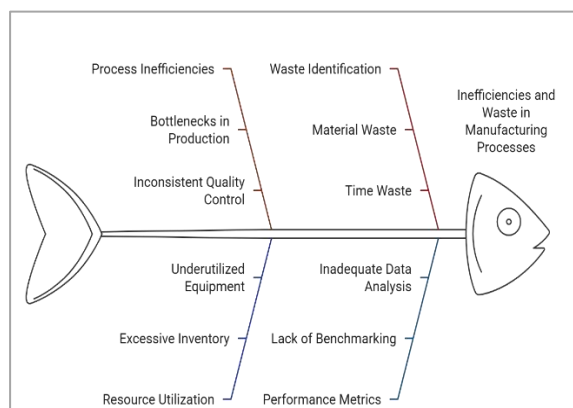


Figure 2. Enhancing Manufacturing Efficiency with Lean Six Sigma.

The overall methodological approach is intended to provide a structured and data-based framework for identifying manufacturing inefficiencies, implementing targeted improvements, and maintaining process gains over time.

3.2. Research Objective

The primary objective of this research is to improve resource efficiency and reduce waste in manufacturing through the application of Lean Six Sigma principles.

The specific objectives are:

- To identify major sources of waste and inefficiency within manufacturing processes.
- To develop a Lean Six Sigma-based framework for improving resource utilization and operational performance.
- To evaluate the applicability of the proposed framework through case-based assessment.
- To establish performance measures for quantifying waste reduction and improvements in manufacturing efficiency.
- To support continuous improvement and long-term operational performance through systematic, data-driven process evaluation.

3.3. Method of Data Analysis

The study uses the following analytical tools within the Lean Six Sigma framework:

- **Six Sigma DMAIC Framework:**

The Define–Measure–Analyze–Improve–Control cycle is used to address identified process inefficiencies systematically.

- **Statistical Process Control (SPC):**

Control charts are used to monitor process variability and identify trends or deviations in relevant process measures.

- **Pareto Analysis:**

Pareto analysis is used to identify the major sources of waste and prioritize areas requiring improvement.

- **Failure Mode and Effects Analysis (FMEA):**

FMEA is used to identify potential process failures and assess their possible effects on manufacturing efficiency.

- **Root Cause Analysis (RCA):**

Techniques such as Fishbone diagrams and the 5 Whys are used to investigate the underlying causes inefficiencies.

The major steps associated with Lean implementation are summarized in Figure 3, while the DMAIC improvement cycle is presented in Figure 4.

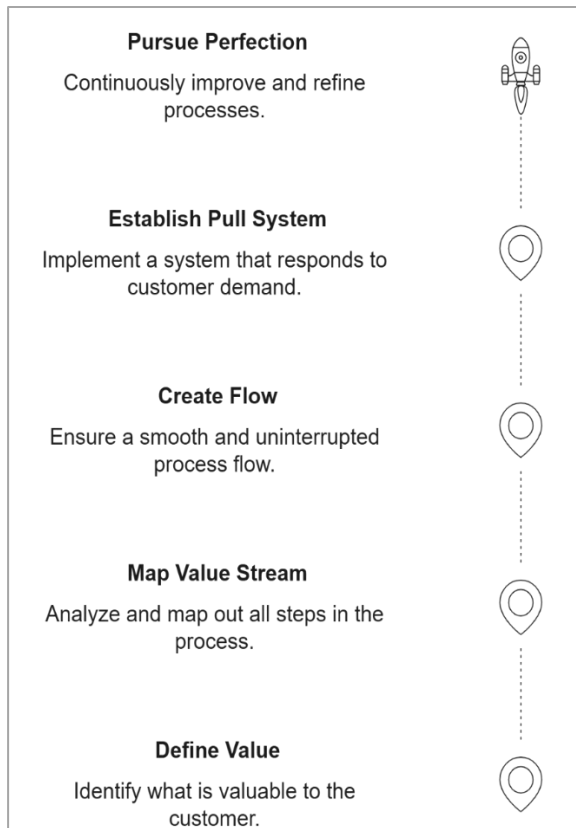


Figure 3: Steps to Lean Excellence

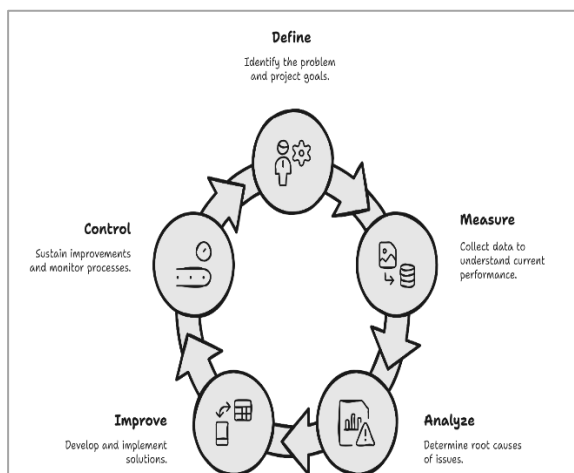


Figure 4: DMAIC Process Cycle

3.4. Evaluation and Justification of Methodological Choices

The selection of Lean Six Sigma is based on its structured combination of process improvement, waste reduction, data-driven analysis, and continuous monitoring. The methodology enables manufacturing processes to be examined systematically while providing mechanisms for identifying inefficiencies, implementing targeted improvements, and monitoring process performance.

The methodological choices are supported by the following considerations:

- **Data-Driven Decision-Making:**

The approach uses measurable process information to identify inefficiencies and support targeted improvement decisions.

- **Process Efficiency:**

Lean principles focus on eliminating non-value-added activities, reducing unnecessary process steps, and minimizing material losses.

- **Continuous Improvement:**

The DMAIC cycle provides a structured mechanism for identifying problems, implementing improvements, and maintaining process gains.

- **Scalability And Adaptability:**

The framework can be applied to different manufacturing processes and adapted according to process characteristics and organizational requirements.

Through the integration of Lean and Six Sigma principles, the proposed methodology provides a structured approach for evaluating manufacturing processes, reducing waste, improving resource utilization, and supporting sustained process improvement. The major Lean Manufacturing principles and practices considered in the framework are summarized in Figure 5.

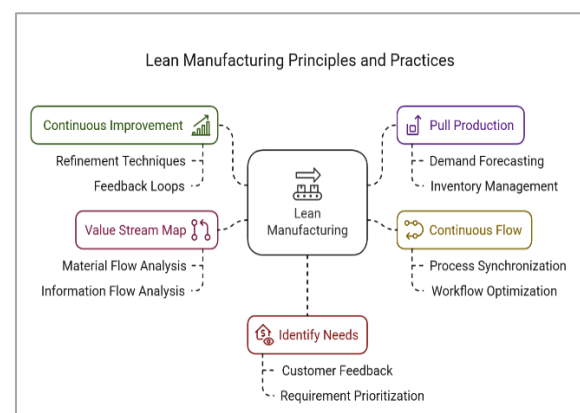


Figure 5. Lean Manufacturing Principles and Practices.

4. Results

The application of the Lean Six Sigma approach resulted in measurable improvements across the evaluated manufacturing process. The major outcomes are presented below in terms of defect reduction, cycle-time improvement, cost savings, customer satisfaction, process capability, and employee engagement. Figure 6 presents the Pareto distribution of the common manufacturing issues considered in the analysis.

4.1. Defect Reduction

The reported defect rate decreased from 12% to 4.5%, corresponding to a 62.5% reduction in defects. The improvement was associated with the application of root cause analysis, standardized work procedures, and error-proofing techniques.

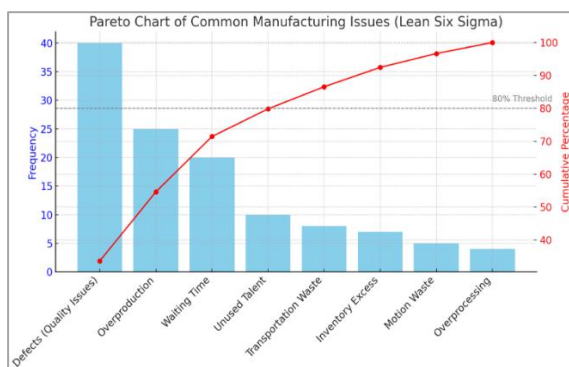


Figure 6. Pareto Chart of Common Manufacturing Issues (Lean Six Sigma).

4.2. Cycle-Time Reduction

The reported process cycle time decreased from 120 minutes to 85 minutes, representing a 29.2% reduction. Value stream mapping and process-flow optimization were used to identify and reduce non-value-added activities contributing to process delays.

4.3. Cost Reduction

The estimated annual cost savings were approximately US\$18,500. The reported savings were attributed to reductions in rework, material waste, and overtime labor.

4.4. Customer Satisfaction

Customer satisfaction increased by 18% following the reported process improvements. The improvement was associated with greater product consistency and reduced delivery time.

4.5. Process Capability

The process capability index (Cpk) increased from 0.95 to 1.45, indicating an improvement in the reported capability of the process to operate within specified requirements.

4.6. Employee Engagement

Employee involvement and ownership also improved following the implementation of the improvement activities. Cross-functional teams participated in identifying process problems and implementing improvement measures, supporting greater involvement in continuous-improvement activities. The reported outcomes of the Lean Six Sigma implementation are summarized in Figure 7.

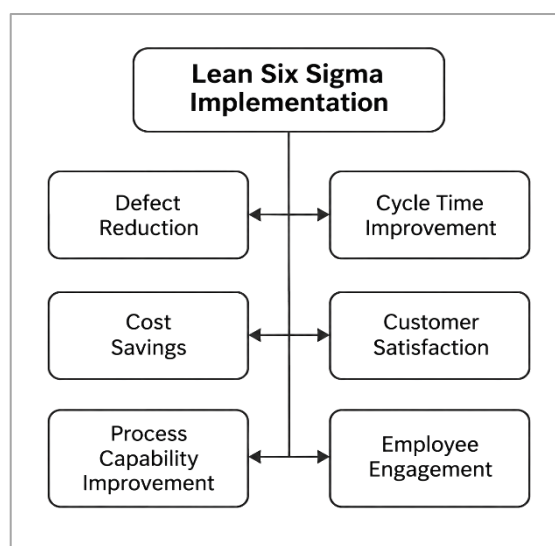


Figure 7. Lean Six Sigma Implementation Outcomes.

Overall, the reported results indicate improvements across multiple manufacturing-performance dimensions, including quality, cycle time, cost, customer satisfaction, process capability, and employee participation. These outcomes are consistent with the intended objectives of the integrated Lean Six Sigma framework and demonstrate its potential to support systematic waste reduction and resource-efficiency improvement.

5. Discussion

The findings indicate that the integrated Lean Six Sigma framework provided a structured approach for addressing process inefficiencies, waste, and quality-related problems in the manufacturing context considered in this study. The observed reduction in defects from 12% to

4.5% demonstrates a substantial improvement in process quality. This improvement can be associated with the combined use of root cause analysis, standardized work practices, error-proofing, and data-driven process monitoring. The result is consistent with the broader application of Lean Six Sigma as a methodology that combines waste elimination with systematic reduction of process variation [5,16,19,20].

The reduction in cycle time from 120 to 85 minutes further indicates that process-flow analysis and Lean-based waste identification can contribute to improved operational efficiency. Value stream mapping and process-flow optimization provide a means of identifying non-value-adding activities, unnecessary movement, waiting, and process delays. The findings therefore support the use of Lean tools as complementary elements within the Six Sigma improvement cycle rather than treating quality and efficiency as separate improvement objectives. Similar applications of Lean and Lean Six Sigma have reported improvements in manufacturing processes through systematic identification and elimination of operational waste [1,3,6,18].

The reported increase in process capability, with Cpk improving from 0.95 to 1.45, indicates improved process performance under the measurement conditions considered in the study. This change is particularly relevant because Six Sigma methods emphasize controlling process variation and maintaining consistent output. The simultaneous reduction in defects and improvement in Cpk suggests that the framework addressed not only visible process waste but also underlying sources of process variation. The reported annual cost saving of approximately US\$18,500 provides an additional indication that improvements in quality and process efficiency can have economic benefits through reductions in rework, material losses, and overtime requirements. However, the financial benefit remains dependent on the assumptions and cost components used in the study's estimation.

The reported 18% improvement in customer satisfaction also indicates a possible relationship between internal process improvements and perceived service or product performance. More consistent production, reduced defects, and shorter processing times can contribute to improved delivery reliability and product consistency. In addition, increased employee involvement reported in the study is relevant to the sustainability of continuous improvement because Lean Six Sigma implementation

generally requires participation across operational and functional levels. The integration of employee involvement with standardized processes, monitoring, and corrective action can support the continuation of improvement activities beyond the initial implementation phase.

The findings also highlight the practical value of integrating multiple improvement tools within a single framework. DMAIC provides the overall improvement structure, while value stream mapping, Pareto analysis, SPC, FMEA, and root cause analysis support specific activities within the improvement cycle. Such integration is consistent with previous research emphasizing the importance of systematic implementation, organizational involvement, and appropriate methodological selection in Lean Six Sigma projects [5,14,17]. Rather than relying on a single improvement technique, the proposed framework provides a sequence through which problems can be defined, measured, analyzed, improved, and controlled.

Despite these positive findings, the results should be interpreted within the scope of the study. The evaluation is based on the manufacturing context considered in the study, and the extent to which the reported improvements can be generalized to other manufacturing environments may depend on process characteristics, organizational conditions, production volume, and implementation practices. In addition, longer-term monitoring would be useful for determining whether the observed improvements are sustained over time. Future studies may therefore apply the framework across different manufacturing processes and larger datasets, while incorporating longer observation periods and more detailed economic and process-performance measures. Such validation would strengthen the assessment of the framework's scalability and its contribution to sustained resource efficiency and continuous improvement.

6. Conclusion

Lean Six Sigma provides an integrated approach that combines the waste-reduction principles of Lean Manufacturing with the process-improvement and variation-reduction principles of Six Sigma. By identifying non-value-added activities, analyzing process variation, and applying data-driven improvement techniques, the approach can support improvements in manufacturing quality, efficiency, and resource utilization.

The framework presented in this study integrates tools such as DMAIC, value stream mapping, Statistical Process Control, Pareto analysis, FMEA, and root cause analysis to provide a structured approach for identifying manufacturing inefficiencies and implementing targeted improvements. The approach also emphasizes continuous monitoring and process control to support the maintenance of improvement gains.

The reported evaluation indicates improvements in defect rate, cycle time, cost efficiency, customer satisfaction, and process capability following the application of Lean Six Sigma. These outcomes support the use of a structured, data-driven approach for addressing manufacturing waste and improving resource efficiency.

Overall, the proposed framework provides a practical basis for systematic process improvement and continuous monitoring in manufacturing environments. Its application can support organizations in identifying sources of waste, improving resource utilization, reducing process inefficiencies, and sustaining improvements through ongoing performance evaluation.

Future work should further evaluate the framework across different manufacturing environments and over longer periods to examine the sustainability and transferability of the reported improvements.

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