

ARTICLE

## Enhancing Cost of Quality in Manufacturing Through Lean Six Sigma: A Case Study

Attia Hussien Gomaa<sup>1,\*</sup>

<sup>1</sup> *Mechanical Engineering Department, Faculty of Engineering, Shubra, Benha University, Cairo, Egypt*

\*Corresponding author. Email: [attia.goma@feng.bu.edu.eg](mailto:attia.goma@feng.bu.edu.eg)

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### Abstract

The Cost of Quality (CoQ) is a critical determinant of competitiveness and operational efficiency in manufacturing. However, CoQ measurement is often disconnected from improvement initiatives, limiting its effectiveness in driving sustained performance gains. This fragmentation—along with inconsistent measurement practices, weak alignment with strategic objectives, sector-specific complexities, and limited data analytics capabilities—restricts the use of CoQ as a strategic decision-making tool. This study proposes an integrated Lean Six Sigma (LSS)-based framework that bridges CoQ measurement and continuous improvement execution. The framework combines standardized CoQ metrics, strategic alignment, and LSS methodologies within a data-driven structure that enables systematic identification, analysis, and reduction of quality-related costs. It further embeds continuous improvement into operational routines, supporting proactive and evidence-based decision-making. The framework is validated through a case study of an Egyptian electrical control panel manufacturer. Implementation aligned strategic objectives with measurable key performance indicators (KPIs) and targeted interventions, achieving substantial improvements: internal failure costs decreased by 33–42%, external failure costs by 33–40%, and overall CoQ by 41.7%. Additionally, process reliability improved by 20.6%, first-pass yield increased by 18.3%, lead time decreased by 28.6%, and unit production costs declined by 20.8%. These results demonstrate that the proposed framework offers a scalable and empirically validated approach for integrating CoQ management with LSS, enhancing cost efficiency and strengthening data-driven decision-making in manufacturing operations.

**Keywords:** Cost of Quality; Lean Six Sigma; Manufacturing Operations; Quality Management; Operational Performance; Continuous Improvement

### 1. INTRODUCTION

In today's highly competitive manufacturing environment, organizations face increasing pressure to enhance efficiency, reduce costs, and meet rising customer expectations. In this context, the Cost of Quality (CoQ), encompassing the costs of preventing, detecting, and correcting defects, serves as an important mechanism for improving both operational performance and strategic outcomes. Effective CoQ management can reduce waste and rework, enhance process reliability and product quality, and support overall profitability. However, despite its recognized relevance, many organizations continue to face challenges in systematically measuring and controlling quality-related costs, often relying on fragmented and reactive practices that are not fully aligned with strategic objectives [1]. Consequently, Quality Cost Management (QCM) has become an integral element of Quality Management Systems (QMS), supporting organizations in quantifying and addressing quality-related inefficiencies through structured improvement efforts [2]. QCM encompasses both costs of conformance prevention and appraisal and costs of non-conformance, including internal and external failures [3], and its effectiveness is closely linked to organizational maturity, as maturity models facilitate capability assessment, benchmarking, and continuous improvement [4]. Nevertheless, the application of CoQ as a strategic management tool remains uneven, particularly in the agrifood sector [5,6], where organizations may

underestimate actual quality costs and lack dedicated systems for the systematic measurement and evaluation of CoQ [7,8].

### **1.1. Cost of quality (CoQ) and the PAF model**

The Prevention Appraisal Failure (PAF) model provides a structured and widely adopted framework for analyzing and managing CoQ. As presented in Table 1 and illustrated in Figure 1, CoQ is categorized into prevention, appraisal, internal failure, and external failure costs [9-11]. Prevention costs involve proactive measures such as quality planning, employee training, process improvement, supplier development, and preventive maintenance, while appraisal costs relate to inspection and testing activities aimed at detecting defects before delivery. Internal failure costs arise from defects identified before reaching customers and include rework, scrap, and downtime, whereas external failure costs occur after delivery and include returns, complaints, recalls, and reputational damage [12-15]. Although prevention and appraisal costs typically represent a smaller share of total CoQ, they can be viewed as strategic investments that help reduce downstream failure costs and enhance process stability. Strengthening these activities supports improved decision-making, more efficient resource allocation, and closer alignment between quality initiatives and organizational objectives [16,17]. In agrifood sectors, where strict quality requirements must be balanced with efficiency and cost considerations, systematic CoQ measurement can provide valuable insights into process performance and support evidence-based decision-making [18,19].

### **1.2. Lean six sigma: Conceptual foundations and methodological structure**

Lean Six Sigma (LSS) integrates Lean principles with Six Sigma methodologies to provide a structured approach for improving efficiency, quality, and cost performance through the elimination of waste and reduction of process variability [20-22]. Lean focuses on removing non-value-added activities and improving workflow efficiency, while Six Sigma applies statistical methods to reduce variation and defects; together, they contribute to enhanced process stability and overall organizational performance [23-26]. Originating from the Toyota Production System and Motorola, respectively, has resulted in a unified methodology applicable across manufacturing and service contexts [27-29]. LSS is commonly implemented through the DMAIC framework, Define, Measure, Analyze, Improve, and Control which supports systematic and data-driven improvement: Define establishes objectives and critical-to-quality (CTQ) characteristics; Measure validates baseline performance; Analyze identifies root causes; Improve develops and implements solutions; and Control sustains improvements through standardization and monitoring [30-33]. Evidence from prior studies indicates that LSS contributes to improvements in quality, efficiency, and customer satisfaction across manufacturing, healthcare, and service sectors [34-37], while also supporting supply chain performance and alignment with standards such as ISO 9001 [38-41]. In engineering and project management contexts, LSS has been associated with reduced defects, delays, and rework, as well as improved delivery performance and resource utilization [42-44].

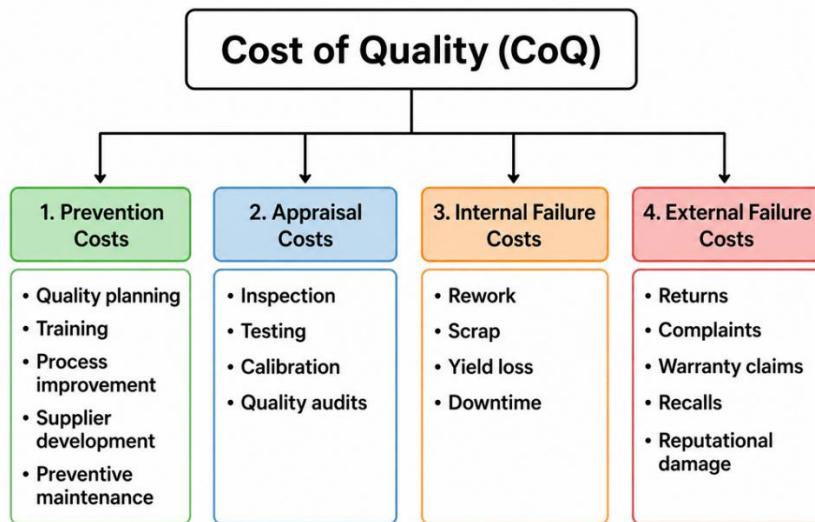
### **1.3. Study objectives and contributions**

Despite its potential, CoQ management is often not fully integrated with structured improvement methodologies such as LSS, which may limit its effectiveness in supporting continuous improvement. This study addresses this gap by developing a systematic LSS-based framework for CoQ management in manufacturing operations, including a review of existing practices, identification of research and implementation gaps, development of a structured framework to minimize quality-related costs while embedding continuous improvement, and validation through a real-world case study. Building on Gomaa [33], the study contributes by providing a comprehensive and empirically grounded approach that links theoretical concepts with practical application and offers useful insights for both researchers and practitioners.

The paper is organized as follows: Section 2 reviews CoQ, maturity models, and identifies gaps; Section 3 presents the proposed framework; Section 4 demonstrates its application through a case study; and Section 5 discusses implications and directions for future research.

**Table 1.** Categories of cost of quality (CoQ).

No	Category	Definition	Representative costs	Operational impact	Industry examples
1	Prevention Costs	Actions and investments to prevent defects and ensure quality	Process redesign, training, preventive maintenance, quality planning	Reduces defects and rework, improves efficiency, and strengthens customer trust	Manufacturing: Six Sigma; Service: Training programs; High-tech: QA design & validation
2	Appraisal Costs	Activities to identify defects before delivery	Inspections, audits, testing, calibration, process verification	Detects errors early, ensures compliance, and reduces downstream failures	Manufacturing: Final inspections; Service: Audits; Healthcare: Lab verification
3	Internal Failure Costs	Costs from defects detected before reaching customers	Rework, scrap, downtime, corrective actions	Causes delays, consumes resources, lowers productivity	Manufacturing: Faulty assembly; Service: Order errors; High-tech: Software bug fixes
4	External Failure Costs	Costs from defects reaching customers	Warranty claims, returns, recalls, complaints	Damages reputation, reduces satisfaction, increases liability	Manufacturing: Recalls; Service: Refunds/complaints; High-tech: System failures



**Figure 1.** Categories of cost of quality (CoQ).

## 2. Literature Review

This study conducts a systematic literature review (SLR) of peer-reviewed publications from 2010 to 2026, retrieved from Scopus, Web of Science, and Google Scholar. The search employed targeted keywords, including “Cost of Quality (CoQ),” “manufacturing operations,” “Lean Six Sigma,” “quality management,” “operational efficiency,” and “quality improvement.” The review critically examines the current state of research on CoQ management in manufacturing, explores the integration of Lean Six Sigma (LSS) for process and quality improvement, and identifies gaps in both theoretical understanding and practical application. By synthesizing prior studies, it establishes a foundation for developing a structured CoQ management framework and highlights areas requiring further research to enhance operational efficiency, quality performance, and strategic outcomes.

Cost of Quality (CoQ) management has evolved from an accounting measure into a strategic enabler, linking operational performance, financial outcomes, and customer satisfaction [15,45]. Systematic measurement and mitigation of quality-related costs allow organizations to identify inefficiencies, reduce waste, optimize resources, and enhance profitability [6,46]. Defects and process failures generate financial losses, reputational damage, customer dissatisfaction, and operational disruptions, undermining long-term competitiveness. Evidence highlights the role of organizational maturity: Barakat and Ellassimi [1] reported that Moroccan agri-food companies with higher quality management maturity (QMM) adopt CoQ practices systematically, prioritizing prevention and continuous improvement. Similarly, Essien and Samuel [47] found that CoQ implementation in Nigerian banks, including internal controls, failure

prevention, and appraisal, improved operational performance, reduced defects, and enhanced customer satisfaction.

### **2.1. Cost of Quality: Categories and Framework**

CoQ is categorized into prevention, appraisal, internal failure, and external failure costs [48]. Prevention costs include employee training, process improvement, and supplier development; appraisal costs involve inspections, testing, and audits; internal failures are defects detected before delivery; and external failures occur when defective products or services reach the customer. This classification enables strategic resource allocation, investment planning, and continuous improvement, transforming quality management from a reactive cost center into a proactive, value-creating function.

The PAF model, formalized by Juran and Gryna [49] and Feigenbaum [50] and refined by Crosby [51], distinguishes conformance and non-conformance costs, and emphasizes proactive quality management [5,15]. Advanced approaches integrating failure mode costs with FMEA, Monte Carlo simulations, and fuzzy logic link defect probability and severity to financial impact, supporting risk-aware decisions [52]. Despite some criticisms, PAF remains widely adopted for its clarity and practical utility [53-56] and forms the theoretical basis for this study [57-59].

Organizational maturity is essential for effective CoQ management. Maturity models provide frameworks to evaluate process sophistication, identify improvement opportunities, and benchmark performance [4]. They shift organizations from reactive problem-solving to proactive, integrated quality strategies embedded in culture and operations, enhancing sustainability and CoQ effectiveness. Despite these advantages, adoption is uneven. Many organizations limit CoQ to isolated quality activities rather than embedding it into comprehensive performance management systems [60,61]. Sectoral coverage is uneven: manufacturing and services are relatively well-studied, while the agrifood sector, especially in developing economies, remains underexplored [62], reducing CoQ's relevance to local operational realities and constraints.

### **2.2. Integrating CoQ with Lean Six Sigma**

Integrating CoQ with Lean Six Sigma (LSS) enhances its practical impact by combining waste elimination, process standardization, and statistical quality control with cost management. Lean tools such as value stream mapping and Kaizen events identify non-value-added activities, while Six Sigma reduces variation and prevents defects, lowering internal and external failure costs [15,45]. This integration establishes measurable, cost-effective continuous improvement cycles aligned with strategic objectives, bridging the gap between quality measurement and operational execution. Mature LSS systems also improve sustainability by reducing resource consumption, minimizing waste, and mitigating environmental impacts [45,63]. CoQ assessment methodologies include top-down strategic benchmarking, bottom-up operational decision-making, and hybrid models [64], event-based failure analysis [65], and Taguchi's quality loss function [66]. Collectively, these approaches show that CoQ is not merely a cost-monitoring tool but a strategic driver of operational excellence and competitive advantage [2,3].

Lean Six Sigma combines Lean and Six Sigma to enhance efficiency, reduce waste, and improve process performance [67,68]. Lean eliminates non-value-added activities, streamlines workflows, standardizes processes, and optimizes resources [69], while Six Sigma applies statistical methods to minimize variation, improve quality, and strengthen operational outcomes [42,70]. Integration with ISO 9001 ensures standardized processes, strategic alignment, and measurable performance outcomes [44,71]. Lean principles define customer value, map value streams, create flow, establish pull, and pursue perfection, while Six Sigma's DMAIC framework (Define, Measure, Analyze, Improve, Control) provides a structured, repeatable, and data-driven approach [34-37].

Lean focuses on workflow stabilization, waste elimination, and process standardization to improve efficiency, competitiveness, and resilience [72,73]. When combined with JIT, TQM, TPM, and HRM, it strengthens product quality, reliability, and employee engagement [74-76]. Tools such as 5S, SMED, Kanban, Kaizen, and Poka-Yoke operationalize Lean principles, promoting standardization, continuous improvement, flow efficiency, and defect prevention [77-81].

Six Sigma complements Lean by systematically identifying root causes, reducing variation, and improving consistency and reliability [82-85]. It has demonstrated improvements in productivity, quality,

and customer satisfaction across sectors [86,87], while DMAIC guides organizations from problem identification to solution implementation and performance evaluation [88-90].

LSS optimizes production, inventory, and cost efficiency [3,20]. Lean eliminates waste and standardizes workflows, while Six Sigma reduces variation and defects, lowering costs in design, development, and manufacturing and conserving labor, materials, and management resources [91-95]. Embedded inventory and transport practices improve operational capability, turnover, stock management, and reduce bottlenecks [96,97].

LSS drives financial gains through defect reduction, productivity improvements, higher profit margins, and enhanced returns on assets and sales [98-100], while fostering a culture of continuous improvement, collaboration, and employee engagement [101,102]. Lean encourages creative problem-solving, and Six Sigma emphasizes root-cause analysis, cross-functional collaboration, and data-driven decision-making [103-105]. DMAIC and DFSS provide structured, replicable approaches to implement innovative solutions [106]. Combined, Lean and Six Sigma reduce emissions, minimize waste, optimize resources, and strengthen corporate reputation [107-110].

LSS has proven effective across manufacturing, healthcare, food processing, laboratories, and financial services, stabilizing processes, reducing errors, and improving quality and workflow efficiency [111-118]. Maximum benefits occur when defect reduction and process optimization are pursued together, supported by structured implementation, ISO 9001 alignment, and sustainability integration [110,119].

In conclusion, Lean Six Sigma provides a comprehensive, data-driven framework integrating efficiency, quality, cost control, innovation, and sustainability. By combining Lean waste elimination with Six Sigma rigor, LSS enables measurable improvements in productivity, operational performance, financial outcomes, customer satisfaction, and environmental stewardship, embedding continuous improvement, collaboration, and innovation into daily [33, 41].

### **3. Challenges and Research Gaps Analysis**

Despite extensive theoretical development, manufacturing organizations continue to face significant challenges in implementing Cost of Quality (CoQ) practices effectively, especially when integrated with Lean Six Sigma (LSS). A central challenge is the accurate measurement and categorization of quality costs. Although frameworks such as the Prevention–Appraisal–Failure (PAF) model provide structure, many organizations struggle to account for hidden and indirect costs, including opportunity losses, reputational damage, regulatory penalties, and supply chain disruptions [52,120]. Inconsistent measurement approaches across sectors further reduce the reliability, comparability, and strategic value of CoQ data, limiting its usefulness for both operational and enterprise-level decision-making [2,53,55].

Integrating CoQ with Lean Six Sigma introduces additional complexities. While LSS is recognized for reducing process variation, eliminating waste, and improving efficiency [67,68], its practical application alongside CoQ metrics is often fragmented. Many manufacturers lack the necessary data infrastructure, cross-functional coordination, and structured methodologies to link CoQ insights directly to process improvement initiatives [15,45]. Consequently, CoQ management often remains reactive, limiting its potential to support cost-effective continuous improvement. For example, a Six Sigma project may successfully reduce defect rates, but without quantifying associated CoQ savings, organizations cannot capture the full financial or strategic impact of quality initiatives [46,121].

Strategic alignment is another critical challenge. CoQ initiatives are frequently confined to quality or operational teams rather than integrated into enterprise-wide performance management systems [3,10]. Without this alignment, quality improvements may enhance product reliability yet fail to optimize resource allocation, risk management, and long-term profitability [4,5]. Embedding CoQ into organizational strategy is essential for maximizing its value and supporting sustainable competitive advantage.

Sector-specific factors further limit CoQ adoption. Industries with complex production processes, high variability, and strict regulatory requirements such as automotive, electronics, pharmaceuticals, and high-tech manufacturing struggle to standardize CoQ practices and forecast quality costs accurately [6,54]. Manufacturers with short product life cycles or fluctuating demand face additional challenges, limiting the predictive and preventive potential of CoQ [7,62]. Empirical research on CoQ integration with LSS in these contexts remains sparse, resulting in limited actionable, sector-specific guidance [57,60].

Organizational maturity is a key determinant of CoQ effectiveness. Low-maturity organizations often rely on reactive problem-solving, with weak integration of CoQ into operational routines and LSS initiatives. Maturity models provide structured approaches to assess capabilities, benchmark performance,

and guide proactive quality strategies; however, their practical application in manufacturing remains limited [4,11]. Low-maturity firms struggle with consistent measurement, linking CoQ to process improvements, and leveraging insights for enterprise-level decisions [1,47]. High-maturity organizations, in contrast, systematically track CoQ, foster cross-functional collaboration, and make evidence-based decisions, enhancing the strategic value of quality initiatives.

Data management and analytics pose additional challenges. Advanced CoQ frameworks require integrating multiple sources, including production metrics, defect logs, inspection records, and financial data [64,65]. Without real-time analytics, standardized reporting, and centralized dashboards, insights are delayed or incomplete, limiting timely corrective and preventive actions. These challenges are particularly significant in multi-site or global operations, where consistent data collection and reporting are essential for effective CoQ management [45,66]. Digital tools, IoT-enabled monitoring, and enterprise analytics platforms can address these gaps, but adoption remains uneven.

Human factors and organizational culture also influence CoQ adoption. Resistance to change, limited cross-functional collaboration, and insufficient expertise in CoQ and LSS methodologies can impede implementation [101,102,122]. Successful initiatives require strong leadership support, employee engagement, and a culture that prioritizes continuous improvement and accountability. Organizations that integrate CoQ with strategic objectives, align it with LSS practices, and cultivate a data-driven culture are better positioned to achieve sustainable improvements in quality, cost efficiency, and operational performance.

In summary, Table 2 provides a concise overview of the key challenges and research gaps in CoQ management using Lean Six Sigma, along with actionable recommendations. The table emphasizes the importance of standardized measurement, integrated CoQ–LSS frameworks, strategic alignment, sector-specific adaptation, organizational maturity, robust data analytics, and supportive organizational culture. Collectively, these insights highlight the need for a comprehensive, structured framework that bridges theory and practice, enabling manufacturers to optimize operational efficiency, reduce costs, enhance quality performance, and achieve sustainable competitive advantage [2,3,5].

**Table 2.** Challenges and research gaps in managing CoQ using lean six sigma.

No.	Challenge	Implications	Strategic recommendations
1	Inconsistent CoQ measurement	Hidden costs overlooked, reducing decision-making effectiveness.	Standardize measurement and capture all cost categories.
2	Fragmented LSS integration	CoQ data not linked to process improvement, limiting efficiency gains.	Integrate CoQ metrics with Lean Six Sigma and continuous improvement cycles.
3	Limited strategic alignment	Siloed initiatives restrict enterprise-level benefits.	Align CoQ with organizational strategy and performance systems.
4	Sector-specific complexity	High variability and strict regulations challenge forecasting and standardization.	Customize CoQ frameworks for sector requirements and use predictive analytics.
5	Low organizational maturity	Reactive practices reduce CoQ effectiveness and sustainability.	Use maturity models to benchmark performance and embed proactive quality practices.
6	Data and analytics limitations	Fragmented or delayed data slows corrective and preventive actions.	Centralize data, implement real-time analytics, and standardize reporting.

#### 4. Research Methodology

Effective management of the Cost of Quality (CoQ) in manufacturing requires a structured, data-driven approach that integrates defect prevention, operational efficiency, and strategic alignment. This study adopts a Lean Six Sigma (LSS)–based methodology to provide a comprehensive framework for identifying, measuring, analyzing, and reducing quality-related costs while enhancing overall process performance. By combining Lean’s focus on waste elimination with Six Sigma’s statistical rigor, organizations can transform CoQ from a reactive accounting metric into a strategic lever for operational excellence, cost efficiency, and competitive advantage. The methodology emphasizes both proactive prevention of defects and reactive control of failures, ensuring CoQ management supports continuous improvement, resource optimization, and alignment with organizational objectives

##### 4.1. Lean Six Sigma DMAIC Framework for Managing the Cost of Quality

Integrating Lean Six Sigma with CoQ management offers a structured approach to systematically reduce quality costs and improve process performance. The DMAIC (Define-Measure-Analyze-

Improve-Control) methodology connects CoQ metrics to operational processes, performance indicators, and strategic objectives, enabling organizations to identify inefficiencies, prioritize improvement initiatives, and achieve measurable results [42].

In the Define phase, organizations identify high-cost processes and quality priorities, engage cross-functional stakeholders, and establish project scope and objectives. Activities include selecting CoQ categories prevention, appraisal, internal failure, and external failure and defining relevant KPIs. Tools such as Value Stream Mapping (VSM), process flowcharts, and project charters help visualize processes, identify bottlenecks, and prioritize areas with the greatest impact on CoQ. For example, VSM in an electronics line may reveal redundant inspections or excessive waiting times, guiding interventions to reduce appraisal and internal failure costs.

The Measure phase focuses on accurate data collection and validation, quantifying costs across all CoQ categories, including hidden and indirect costs such as scrap, rework, warranty claims, customer complaints, downtime, and lost opportunities. Process mapping, time studies, digital monitoring systems, and dashboards establish a reliable baseline for benchmarking and prioritizing improvements.

During the Analyze phase, organizations investigate the root causes of quality costs and process inefficiencies. Tools, including Root Cause Analysis (RCA), Fishbone (Ishikawa) diagrams, Pareto charts, FMEA, and Statistical Process Control (SPC), allow teams to identify primary drivers of defects, waste, and high-cost failures. Integrating CoQ data with Lean metrics such as process cycle efficiency, defect rates, and waste ensures improvements are prioritized based on operational and financial impact. For instance, RCA and Fishbone analysis in a food processing plant may reveal that operator skill gaps and temperature control failures drive most internal failure costs, guiding targeted corrective actions.

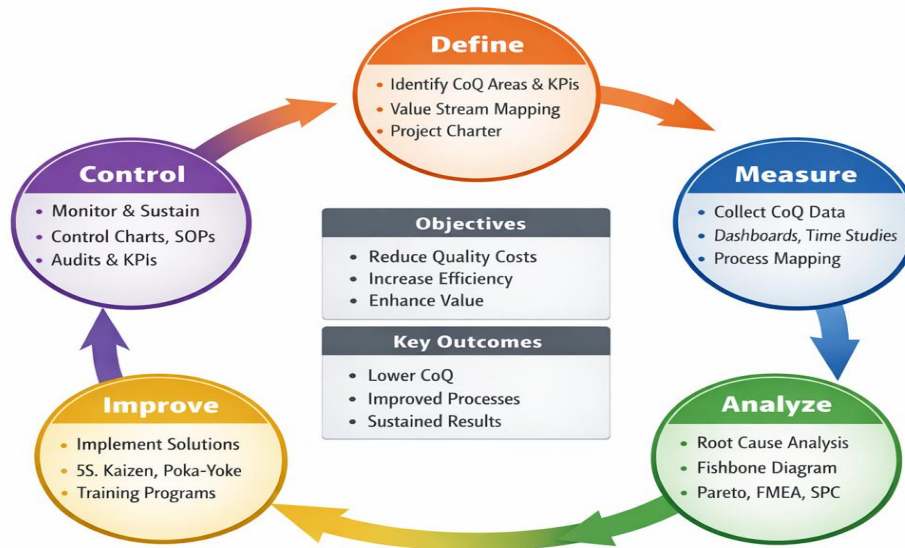
The Improve phase implements solutions to reduce CoQ and enhance performance. Strategies include process standardization, automation, error-proofing (poka-yoke), employee training, supplier development, and Lean initiatives such as 5S, Kaizen, and VSM-driven process redesign. Pilot testing, simulation, and iterative refinement ensure improvements are effective and sustainable, reducing defects, preventing recurring failures, optimizing resource use, and enhancing operational efficiency.

The Control phase sustains improvements through continuous monitoring using SOPs, dashboards, control charts, KPIs, audits, and periodic reviews. Embedding CoQ tracking into daily operations fosters a culture of continuous improvement and aligns CoQ management with strategic objectives. Linking control mechanisms to Lean Six Sigma governance creates a robust feedback loop, supporting long-term quality performance and cost reduction.

Table 3 and Figure 2 summarize the DMAIC framework, linking each phase to core activities, objectives, key outcomes, and tools. This structured approach ensures systematic identification, measurement, analysis, improvement, and control of quality costs while supporting operational efficiency and strategic decision-making.

**Table 3. DMAIC Framework for managing the cost of quality.**

Phase	Core activities	Objectives	Key outcomes	Key tools
Define	Identify critical processes, CoQ categories, KPIs; engage stakeholders; map processes	Align CoQ initiatives with strategic goals; prioritize high-impact areas	Clear scope; shared understanding; defined priorities	Value Stream Mapping, process maps, project charters
Measure	Collect and validate CoQ data; quantify prevention, appraisal, internal, and external failure costs; capture hidden/indirect costs	Establish an accurate baseline; ensure data reliability	Reliable CoQ baseline; identification of cost-intensive processes; measurable metrics	Dashboards, time studies, process mapping, digital monitoring
Analyze	RCA, Fishbone diagram, Pareto, FMEA, SPC; integrate CoQ with Lean metrics	Identify drivers of quality costs; prioritize improvement opportunities	Insight into defect sources; high-cost areas highlighted; targeted improvement plan	RCA, Fishbone, Pareto, FMEA, SPC
Improve	Implement process improvements: standardization, automation, error-proofing, training, supplier development, Lean initiatives	Reduce defects, waste, and CoQ; enhance process efficiency	Lower CoQ; improved process performance; sustainable corrective actions	5S, Kaizen, VSM redesign, poka-yoke, training programs
Control	Monitor performance via SOPs, dashboards, control charts, KPIs; embed CoQ tracking	Sustain improvements; prevent recurrence; institutionalize CoQ management	Long-term gains maintained; proactive CoQ management; alignment with strategy	SOPs, dashboards, control charts, audits, KPIs



**Figure 2.** DMAIC framework for managing the cost of quality

#### 4.2. Strategic Objectives and KPIs for Proactive CoQ Management

Proactive management of the Cost of Quality (CoQ) requires aligning strategic objectives with actionable strategies, measurable KPIs, and expected outcomes. Lean Six Sigma (LSS) provides a structured methodology to implement these objectives systematically, enabling organizations to reduce quality-related costs, enhance operational efficiency, and deliver high-quality products while aligning quality initiatives with organizational goals. Table 4 summarizes the strategic objectives and KPIs.

1) **Minimize Internal Failure Costs:** Internal failure costs result from defects detected during production. Strategies include in-process inspections, defect prevention programs, FMEA, and root cause analysis (RCA). KPIs such as internal defect rate, rework cost, scrap rate, and first-pass yield track performance, leading to reduced rework, lower scrap, and smoother production flows.

2) **Minimize External Failure Costs:** External failure costs arise when defective products reach customers, generating returns, warranty claims, and complaints. Strategies include enhanced product testing, customer feedback analysis, supplier quality management, and warranty monitoring. KPIs such as warranty claims, complaint rate, return rate, and external failure cost enable organizations to improve customer satisfaction and protect brand reputation.

3) **Reduce Overall Quality Costs:** This objective integrates internal and external CoQ components through LSS initiatives, continuous monitoring, and cost-benefit analysis. KPIs such as total CoQ as a percentage of revenue, CoQ breakdown, and cost per defect support optimized resource allocation and measurable savings.

4) **Improve Process Reliability:** Stabilizing production processes involves workflow standardization, control charts, preventive maintenance, and Kaizen events. KPIs, including process cycle efficiency, downtime, and process capability index (Cpk), reduce variability and operational disruptions.

5) **Enhance Product Quality:** Ensuring compliance with customer and regulatory requirements relies on FMEA, RCA, SPC, employee training, and poka-yoke systems. KPIs such as defect rate, first-pass yield, customer satisfaction score, and product conformity rate support continuous quality improvement.

6) **Optimize Operational Efficiency:** Waste elimination and improved resource utilization are achieved through value stream mapping, bottleneck removal, Lean improvements, and 5S practices. KPIs like throughput, lead time, resource utilization, and on-time delivery measure efficiency gains and operational improvements.

7) **Minimize Production Costs:** Overall cost reduction focuses on minimizing scrap and rework, improving energy efficiency, optimizing inventory, and preventive maintenance. KPIs such as cost per

unit, energy consumption, inventory turnover, and production cost variance support profitability and sustainable operations.

In conclusion, Lean Six Sigma-based proactive CoQ management enables organizations to systematically reduce quality-related costs, improve process reliability, and enhance overall operational performance. By focusing on seven strategic objectives, minimizing internal and external failures, reducing total quality costs, improving reliability, enhancing product quality, optimizing efficiency, and lowering production costs, organizations can effectively align quality initiatives with strategic goals. With clearly defined KPIs, this framework supports data-driven decision-making, fosters continuous improvement, and drives sustainable operational excellence.

**Table 4.** Strategic objectives and KPIs for proactive CoQ management.

No.	Objective	Strategies	KPIs	Outcomes
1	Minimize internal failure costs	In-process inspections, defect prevention, FMEA, RCA	Defect rate, Rework cost, Scrap rate, First-pass yield	Lower rework/scrap, improved efficiency
2	Minimize external failure costs	Product testing, customer feedback, supplier quality, warranty monitoring	Warranty claims, Complaints, Returns, External failure cost	Fewer complaints/returns, higher satisfaction
3	Reduce total quality costs	Lean Six Sigma, CoQ monitoring, cost-benefit analysis	Total CoQ (% revenue), CoQ breakdown, Cost per defect	Optimized resources, measurable savings
4	Improve process reliability	Standardized workflows, control charts, preventive maintenance, Kaizen	Cycle efficiency, Downtime, Cpk	Stable processes, fewer disruptions
5	Enhance product quality	FMEA, RCA, SPC, training, poka-yoke	Defect rate, First-pass yield, Customer satisfaction, Conformity rate	Higher quality, fewer defects, stronger trust
6	Optimize operational efficiency	Value Stream Mapping, bottleneck removal, Lean, 5S	Throughput, Lead time, Resource use, On-time delivery	Faster production, less waste, better utilization
7	Minimize production costs	Scrap/rework reduction, energy efficiency, inventory optimization, and preventive maintenance	Cost/unit, Energy/unit, Inventory turnover, Cost variance	Lower costs, improved profitability

## 5. Case Study and Results: Implementation of the Proactive CoQ Framework

This case study demonstrates the practical application of a proactive Cost of Quality (CoQ) framework in an Egyptian electrical control panel manufacturer serving both domestic and regional industrial markets [33]. By integrating Lean Six Sigma (LSS) methodologies with structured CoQ management, the organization systematically identified, measured, analyzed, and mitigated quality-related costs across all CoQ categories—prevention, appraisal, internal failure, and external failure—while embedding process improvements within strategic objectives. This approach transformed CoQ from a reactive accounting metric into a strategic driver of operational excellence, cost efficiency, and sustainable competitive advantage. The key insights, challenges, and outcomes are captured in Table 5, Table 6, Table 7 and Figure 3, Figure 4, Figure 5, Figure 6.

### 5.1. Context and Challenges

The manufacturer faced a complex set of operational, quality, compliance, supply chain, human, and strategic challenges. Hidden quality costs, including rework, scrap, unplanned downtime, warranty claims, returns, and administrative overhead, remained largely untracked, limiting effective resource allocation and obscuring the financial impact of inefficiencies. Operational inefficiencies, such as variable cycle times, equipment stoppages, bottlenecks, excessive non-value-added activities, and uneven WIP inventories, disrupted workflow, reduced throughput, and delayed on-time delivery. Redundant inspections and unnecessary material handling extended lead times, while limited preventive maintenance amplified downtime.

Quality and product performance issues included inconsistent process controls, insufficient preventive measures, frequent defects, and high rework rates, leading to elevated internal and external failure costs and undermining customer satisfaction. Compliance challenges, such as variable adherence

to safety and quality standards, fragmented SOPs, incomplete documentation, and insufficient audit readiness, heightened the risk of nonconformities and penalties. Supply chain issues, including inconsistent raw material quality, delayed deliveries, and limited supplier oversight, further disrupted production schedules and increased scrap. Human and organizational challenges, including siloed decision-making, limited cross-functional collaboration, inadequate training, and high turnover, reduced accountability and problem-solving capacity. Strategic gaps, such as reactive quality initiatives and fragmented CoQ data, contributed to recurring inefficiencies and inconsistent product performance.

Table 5 summarizes these challenges, categorizing each by operational and financial impact. By numbering and structuring the challenges, the table clarifies priorities and provides a roadmap for Lean Six Sigma interventions, including Value Stream Mapping (VSM), Root Cause Analysis (RCA), Fishbone diagrams, FMEA, 5S, and Kaizen events, which systematically reduce costs, improve efficiency, and embed proactive CoQ management.

Table 6 presents a structured framework linking key operational problems in manufacturing to strategic objectives and corresponding KPIs. It highlights challenges such as internal defects, rework, customer complaints, product returns, process variability, workflow inefficiency, and high production costs, and aligns each with objectives focused on reducing failures, lowering quality costs, enhancing product and process quality, and improving operational efficiency.

The KPIs including defect rate, first-pass yield, cycle efficiency, process capability (Cpk), throughput, lead time, and total cost of quality (CoQ) allow organizations to monitor performance, evaluate improvements, and maintain accountability. By integrating problems, objectives, and metrics, the table provides a practical roadmap for proactive quality management, data-driven decision-making, continuous improvement, and optimized resource allocation.

**Table 5.** Key challenges and problems in the manufacturing context.

No.	Category	Challenges / Problems	Impact
1	Operational	Variable cycle times, bottlenecks, equipment stoppages, uneven WIP inventories, excessive non-value-added activities	Reduced throughput, delayed on-time delivery, extended lead times, increased operational costs
2	Quality / Product Performance	Inconsistent process controls, insufficient preventive measures, frequent defects, high rework rates, poor integration of quality data	Higher internal and external failure costs, reduced reliability, lower customer satisfaction
3	Regulatory & Compliance	Variability in safety and quality adherence, inconsistent SOPs, incomplete documentation, fragmented audit readiness	Risk of nonconformities, penalties, reputational damage, unreliable compliance reporting
4	Supply Chain / Material	Variability in raw material quality, inconsistent supplier performance, delayed deliveries, limited supplier oversight	Production disruptions, increased scrap, delayed corrective actions
5	Human / Organizational	Limited cross-functional collaboration, siloed decision-making, poor team communication, insufficient training, high turnover	Reduced problem-solving capacity, inconsistent process execution, weak accountability
6	Strategic / Managerial	Reactive quality initiatives, fragmented performance metrics, unaligned CoQ data, ad hoc corrective actions	Recurring inefficiencies, delayed production, inconsistent product performance, limited strategic alignment

**Table 6.** Operational problems, strategic objectives, and KPIs.

No.	Operational problem	Strategic objective	KPI
1	Internal defects and rework	Reduce internal failure costs	Defect rate, Rework cost, Scrap rate, First-pass yield
2	Customer complaints and returns	Reduce external failure costs	Warranty claims, Complaints, Returns, External failure cost
3	High quality costs	Lower total quality costs	Total CoQ (% revenue), CoQ breakdown, Cost per defect
4	Process variability and downtime	Improve process reliability	Cycle efficiency, Downtime, Process capability (Cpk)
5	Product defects and quality issues	Improve product quality	Defect rate, First-pass yield, Customer satisfaction, Conformity rate
6	Workflow inefficiency	Boost operational efficiency	Throughput, Lead time, Resource utilization, On-time delivery
7	High production costs	Reduce production costs	Cost/unit, Energy/unit, Inventory turnover, Cost variance

## 5.2. Practical Implementation of DMAIC for CoQ Management

To systematically reduce quality costs and enhance operational performance, the manufacturer implemented the DMAIC methodology within a proactive CoQ framework. Table 7 provides an overview of DMAIC operationalization, linking each phase to objectives, tools, KPIs, and expected outcomes.

1) During the Define phase, project scope and objectives targeted processes with the highest CoQ impact. Cross-functional teams applied VSM and process flowcharts to visualize end-to-end workflows, identify bottlenecks, eliminate redundancies, and locate sources of internal and external failure costs. KPIs included internal defect rate, rework cost, scrap rate, first-pass yield, customer complaints, warranty claims, and total CoQ as a percentage of revenue. Mapping the assembly line revealed redundant inspections that increased appraisal costs without reducing defects, highlighting workflow simplification opportunities.

2) In the Measure phase, comprehensive data collection quantified all CoQ categories, including hidden costs such as downtime, lost production opportunities, customer dissatisfaction, and administrative overhead. Digital dashboards, time studies, and production logs validated data accuracy and established a reliable baseline. Analysis revealed that internal failure costs were the largest component of CoQ, followed by external failure costs, while prevention and appraisal expenditures were comparatively low, indicating insufficient upstream quality control that generated downstream defects and higher overall costs.

3) The Analyze phase identified root causes of quality issues using RCA, Fishbone (Ishikawa) diagrams, Pareto analysis, FMEA, and SPC, integrating CoQ data with Lean metrics such as process cycle efficiency and defect rates. Fishbone analysis revealed internal failures caused primarily by inconsistent equipment calibration, insufficient operator training, and non-standardized procedures. Pareto charts highlighted a small number of process steps responsible for the majority of defects, and FMEA prioritized corrective actions by severity, occurrence, and detectability, ensuring interventions addressed the most critical cost drivers.

4) During the Improve phase, targeted measures—process standardization, poka-yoke, operator training, supplier quality development, automation, 5S implementation, Kaizen events, and VSM-driven process redesign—were implemented. Pilot testing and iterative refinement ensured sustainability. Specific interventions included recalibrating equipment, standardizing testing procedures, providing operator training, eliminating redundant inspections, and redesigning workflows to reduce waiting times and unnecessary movement. These measures reduced internal defects, minimized rework and scrap, optimized resource allocation, and improved overall production efficiency.

5) The Control phase embedded continuous monitoring through SOPs, dashboards, control charts, KPIs, and periodic audits, reinforcing a culture of continuous improvement. Linking CoQ monitoring to operational and strategic metrics maintained alignment between process efficiency, product quality, and financial objectives.

In conclusion, DMAIC operationalization converted CoQ management into a structured, data-driven methodology, reducing defects, rework, and total CoQ while improving process efficiency, product quality, and customer satisfaction.

**Table 7.** Practical implementation of DMAIC for CoQ management.

DMAIC	Core Activities	Objectives	Key Tools	KPIs	Expected Outcomes
Define	Identify critical processes, CoQ categories, KPIs; engage stakeholders; map workflows	Align CoQ initiatives with strategic goals; prioritize high-impact areas	Value Stream Mapping, process maps, project charters	Internal defect rate, rework cost, scrap rate, first-pass yield, customer complaints, warranty claims	Clear project scope, shared understanding of challenges, aligned strategic priorities
Measure	Collect and validate CoQ data; quantify prevention, appraisal, internal, and external failure costs; capture hidden/indirect costs	Establish accurate baseline; ensure data reliability	Dashboards, time studies, process mapping, digital monitoring	Total CoQ, breakdown of cost categories, downtime, process cycle time	Reliable baseline, identification of cost-intensive processes, measurable metrics

DMAIC	Core Activities	Objectives	Key Tools	KPIs	Expected Outcomes
Analyze	Conduct RCA, Fishbone diagram, Pareto, FMEA, SPC; integrate CoQ with Lean metrics	Identify drivers of quality costs; prioritize improvement opportunities	RCA, Fishbone, Pareto, FMEA, SPC	Process cycle efficiency, defect rates, failure modes	Root causes identified, high-cost areas prioritized, targeted improvement plan
Improve	Implement process standardization, poka-yoke, training, supplier development, 5S, Kaizen, automation	Reduce defects, waste, and CoQ; enhance process efficiency	5S, Kaizen, VSM redesign, poka-yoke, training programs	First-pass yield, scrap rate, rework cost	Lower CoQ, improved process performance, sustainable corrective actions
Control	Monitor performance via SOPs, dashboards, control charts, KPIs; embed CoQ tracking	Sustain improvements; prevent recurrence; institutionalize CoQ management	SOPs, dashboards, control charts, audits, KPIs	Process capability (Cpk), compliance rate, CoQ trends	Long-term gains maintained, proactive CoQ management, alignment with strategy

### 5.3. Results and Discussion

The integrated implementation of Lean Six Sigma and proactive CoQ management yielded substantial operational, financial, and strategic improvements. Figure 3 shows the pre-improvement VSM, where producing a typical panel required 480 minutes, of which only 226 minutes were value-added, resulting in a Value-Added Process Efficiency (VAPE) of 47.1%. Over half of production time consisted of non-value-added activities such as idle time, excessive movement, and rework, driven by inconsistent workflows, fragmented communication, and non-standardized procedures. Figure 4 presents the Ishikawa diagram, identifying root causes including substandard raw materials, irregular machine maintenance, inadequate operator training, and procedural variability.

The improvement plan applied Lean principles alongside the 7S methodology, redesigning the factory layout into a U-shaped flow, standardizing SOPs, enhancing operator training, and implementing preventive maintenance to reduce unplanned downtime. These initiatives reduced production lead time by 35%, from 480 to 310 minutes, and increased VAPE to 66.1%, as illustrated in Figure 5, demonstrating substantial gains in workflow efficiency, process reliability, and resource utilization.

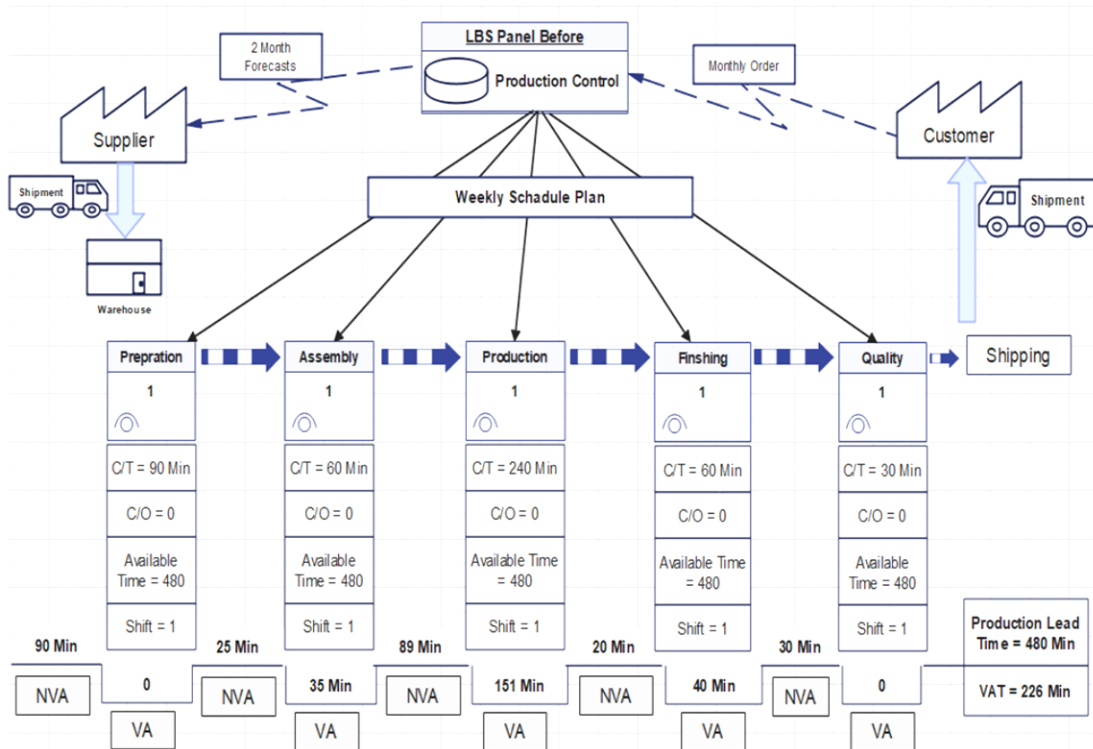
Beyond operational efficiency, these interventions enabled proactive CoQ management. Standardized processes and improved workforce skills allowed accurate identification of internal and external failure costs, minimized scrap and rework, and increased first-pass yield. Structured use of Lean Six Sigma tools including VSM, RCA, poka-yoke, FMEA, and Kaizen initiatives provided a systematic, data-driven approach to eliminate waste, optimize resources, and enhance product quality. By integrating CoQ management with LSS, the organization shifted from reactive corrective measures to proactive, strategic quality management.

Table 8 illustrates the practical application of the proactive CoQ framework, linking strategic objectives to measurable KPIs, targeted interventions, and quantifiable results. Highlights include: reducing internal failure costs by 33–42%, external failure costs by 33–40%, and overall CoQ by 41.7%; improving process reliability by 20.6%; increasing first-pass yield by 18.3%; reducing lead time by 28.6%; and lowering unit production costs by 20.8%.

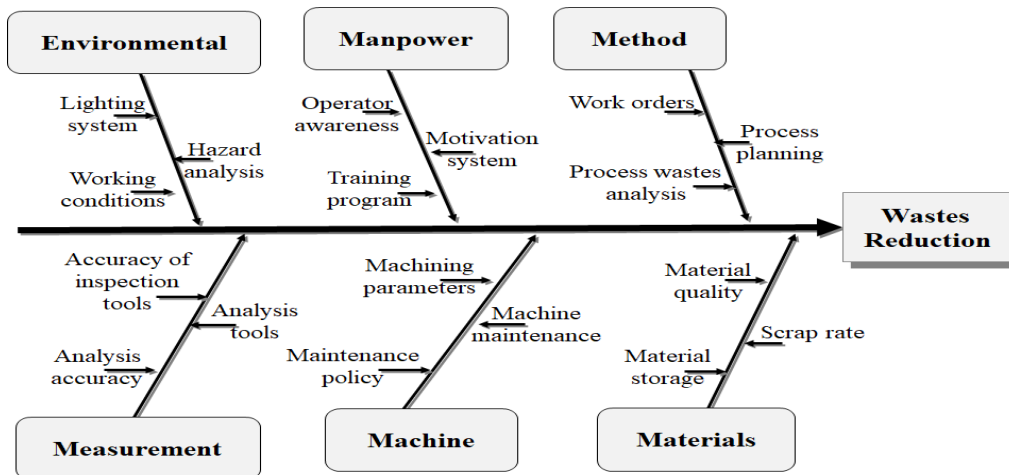
Figure 6 summarizes the measurable impact of these interventions. Production lead time decreased from 480 to 310 minutes, VAPE increased from 47.1% to 66.1%, internal and external failure costs declined, and total CoQ dropped by 41.7%. Operational performance improved significantly, with higher process reliability, increased first-pass yield, reduced lead time, and lower unit production costs.

Overall, integrating Lean Six Sigma with proactive CoQ management transformed quality costs from a reactive accounting measure into a strategic lever for operational excellence, cost efficiency, and sustainable competitive advantage. Through data-driven analysis, structured improvement initiatives, and cross-functional collaboration, measurable gains were achieved across financial, operational, and quality dimensions, while fostering a culture of continuous improvement.

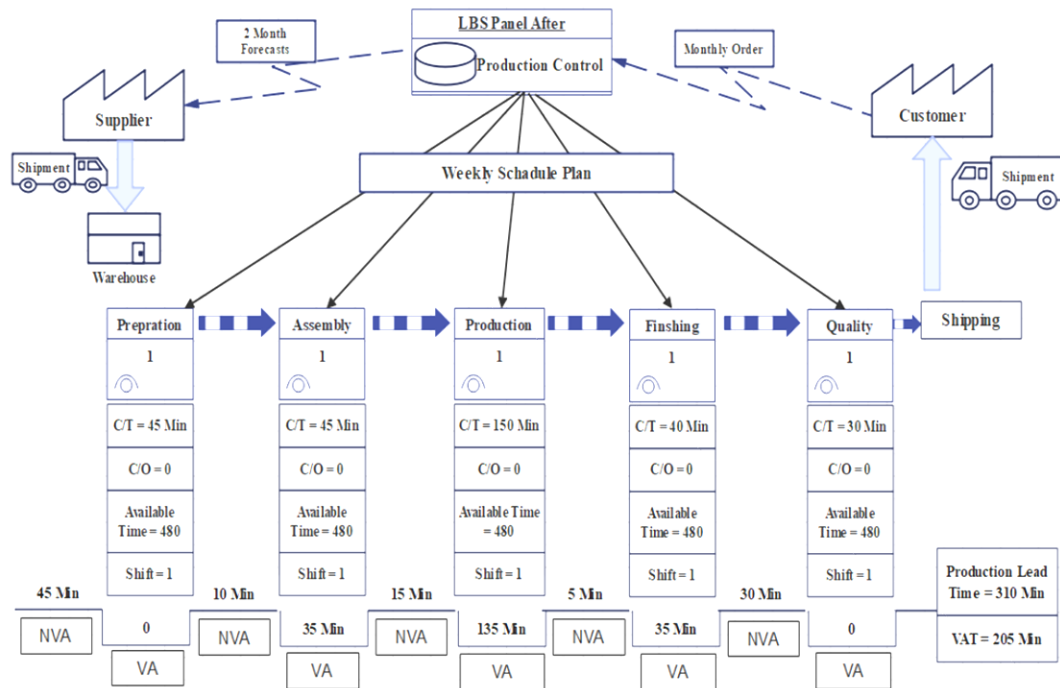
In conclusion, this case study demonstrates that proactive CoQ management supported by Lean Six Sigma delivers tangible operational, financial, and strategic benefits, embeds quality as a strategic priority, and enables sustainable performance improvements, as clearly illustrated in Figures 3 to 6 and Tables 5 to 8.



**Figure 3.** Value stream mapping (before improvement).



**Figure 4.** C&E diagram for non-value-added reduction.



**Figure 5.** Value stream mapping (After improvement).

**Table 8.** Strategic objectives, KPIs, interventions, and performance improvements.

Strategic objective	KPI	Unit	Target	Before	After	Improvement
Minimize internal failure costs	Internal defect rate	%	≤ 3	8	5	-37.5%
	Rework cost	% of production cost	≤ 5	12	7	-41.7%
	Scrap rate	%	≤ 4	6	4	-33.3%
Minimize external failure costs	Warranty claims	# / month	≤ 5	12	8	-33.3%
	Customer complaints	# / month	≤ 10	25	15	-40%
Reduce overall quality costs	Total CoQ	% of revenue	≤ 8	12	7	-41.7%
Improve process reliability	Process cycle efficiency	%	≥ 80	68	82	+20.6%
Enhance product quality	First-pass yield	%	≥ 95	82	97	+18.3%
Optimize operational efficiency	Lead time	Hours/unit	≤ 10	14	10	-28.6%
Minimize production costs	Production cost per unit	\$/unit	≤ 100	120	95	-20.8%



**Figure 6.** Before-and-after impact of LSS on cost of quality.

## 6. Conclusion and Future Work

This study presents a Lean Six Sigma (LSS)-based framework for managing the Cost of Quality (CoQ) in manufacturing, addressing a critical challenge: the difficulty organizations face in systematically measuring, analyzing, and controlling quality-related costs. Ineffective CoQ management can lead to inefficiencies, wasted resources, and missed opportunities for improvement, undermining competitiveness. A structured, data-driven approach that integrates cost management with continuous process improvement is therefore essential for achieving sustainable operational performance.

A comprehensive literature review and gap analysis highlighted key challenges in CoQ management using LSS, including inconsistent measurement practices, fragmented integration with improvement initiatives, and weak alignment with organizational strategy. Additional limitations arise from sector-specific operational complexities, limited organizational maturity, and insufficient data and analytics capabilities. These gaps restrict the ability of organizations to leverage CoQ as a strategic tool for cost reduction and performance enhancement. Addressing them requires standardized measurement frameworks, closer integration with continuous improvement methodologies, strategic alignment, and the adoption of advanced analytics to enable proactive, data-driven decision-making.

The proposed framework provides a structured approach for identifying, measuring, analyzing, and minimizing quality-related costs while embedding continuous improvement into daily operations. By applying Lean Six Sigma principles, it facilitates process optimization, data-driven decisions, and sustainable performance gains.

The framework was validated through a case study of an Egyptian electrical control panel manufacturer serving domestic and regional markets. Linking strategic objectives to measurable KPIs and targeted interventions, implementation achieved substantial improvements: internal failure costs decreased by 33–42%, external failure costs by 33–40%, and overall CoQ by 41.7%. Process reliability improved by 20.6%, first-pass yield increased by 18.3%, lead time decreased by 28.6%, and unit production costs dropped by 20.8%. Beyond these measurable results, the framework fostered a culture of continuous improvement by aligning quality management with Lean Six Sigma practices, supporting long-term operational excellence.

**Theoretical Implications:** This study demonstrates how CoQ measurement can be integrated with DMAIC-based methodologies, including hidden and indirect costs, positioning CoQ as a strategic performance lever rather than a purely operational metric.

**Practical Implications:** The framework provides organizations with structured methods to quantify, monitor, and manage CoQ, optimize preventive and appraisal activities, improve product quality, and enhance resource allocation.

**Managerial Implications:** Managers are guided to align CoQ initiatives with strategic objectives, link quality improvements to profitability, risk mitigation, and compliance, prioritize preventive actions, and leverage quality management as a competitive advantage.

**Study Limitations:** The framework was applied in a single manufacturing firm producing electrical control panels, which may limit generalizability. Adaptation may be required for other industries, and results depend on accurate internal cost-tracking systems.

**Future Research:** Future research should be organized around four key directions to extend the present study and address its limitations.

1) Cross-sector and methodological validation: Future studies should test the proposed Lean Six Sigma–CoQ framework across diverse manufacturing sectors to improve generalizability and capture sector-specific adaptation needs. Multi-case and comparative research designs are recommended to overcome the limitations of the single-case approach and to further refine the framework across different production environments (e.g., engineer-to-order, mass production, and continuous-process systems).

2) Digital transformation and predictive CoQ management: Further research should examine the integration of Industry 4.0 technologies into the DMAIC–CoQ framework. IoT systems can enhance real-time data capture of quality-related cost drivers, AI can support predictive root-cause analysis in the Analyze phase, MES can improve traceability of internal failure costs, and real-time dashboards can strengthen CoQ monitoring and control. These developments can enable a shift from reactive CoQ reporting to predictive and preventive quality management.

3) Organizational and human factors: Future work should explore how leadership commitment, employee engagement, training, and organizational culture influence the success and sustainability of Lean Six Sigma–based CoQ implementation. These factors are critical in ensuring effective DMAIC execution, particularly in sustaining improvements during the Control phase.

Longitudinal and comparative studies: Longitudinal research is needed to evaluate the durability of CoQ reductions and operational improvements over time. In addition, comparative studies between Lean Six Sigma, DMAIC-only applications, and Total Quality Management (TQM) would help identify the most effective approaches for CoQ optimization across different industrial contexts.

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**Abbreviations:**

Abbreviation	Full term	Short definition
CoQ	Cost of Quality	Total cost of ensuring product quality.
DMAIC	Define, Measure, Analyze, Improve, Control	Six Sigma methodology for structured process improvement.
LSS	Lean Six Sigma	Integration of Lean and Six Sigma to improve efficiency and quality.
VAPE	Value-Added Process Efficiency	Percentage of production time spent on value-adding activities.
COPQ	Cost of Poor Quality	Losses from defects, rework, scrap, and nonconformities.
ROQI	Return on Quality Investment	Financial return achieved from quality improvement initiatives.
QMMG	Quality Management Maturity Grid	A tool for assessing and benchmarking organizational quality maturity.
KPI	Key Performance Indicator	Metric used to evaluate performance against objectives.
WIP	Work in Progress	Inventory is currently undergoing production.
SOP	Standard Operating Procedure	Documented process instructions to ensure consistent execution.
CSI	Customer Satisfaction Index	Quantitative measure of customer satisfaction.
SPC	Statistical Process Control	Use of statistical methods to monitor and control process variation.

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