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APPLICATION OF SIX SIGMA METHOD FOR PRODUCT QUALITY CONTROL USING STATISTICAL ENGINEERING APPROACH

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Abstract

This literature study examines the application of Six Sigma methodology with a statistical engineering approach for product quality control in manufacturing industries. Through a qualitative thematic synthesis of academic works and case studies, the analysis addresses two focal points. First, it explores how Six Sigma tools and techniques, including Statistical Process Control, Design of Experiments, and Failure Mode and Effects Analysis, are systematically used to identify production defects, analyze root causes, and design effective improvement solutions. Second, it investigates how Six Sigma implementation contributes to the overall improvement of corporate quality management systems, encompassing enhanced analytical capabilities, cultural transformation toward continuous improvement, integration with existing quality systems, and sustainable control mechanisms. The study concludes that Six Sigma is an effective framework for quality control that requires strong management commitment, organizational readiness, technical competence in statistics and process understanding, and effective change management for successful implementation. Case studies from various industries demonstrate significant improvements in product quality, operational efficiency, and cost reduction. The findings underscore the necessity of integrated approaches combining technical analysis with organizational development to realize the full potential of Six Sigma in improving corporate quality management systems.

Keywords: Six Sigma, quality control, statistical engineering, DMAIC, manufacturing, defect reduction, quality management

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Introduction

Product quality control constitutes one of the fundamental pillars in modern manufacturing operations that determines a company's competitiveness in the global market. Companies capable of producing goods with low defect rates will gain consumer trust, reduce warranty and rework costs, and enhance overall operational efficiency. Conversely, failure in controlling product quality can result in significant financial losses, brand reputation damage, and the loss of market share to more competitive rivals. Quality is no longer merely a technical aspect that falls under the responsibility of the production department, but has become a strategic issue involving the entire organizational value chain (Shehabi, 2022). Findings in small and medium-scale enterprises even indicate that quality control can still be applied effectively despite limited available resources, provided it is accompanied by consistent managerial commitment (Mardikaningsih & Hariani, 2015). In an increasingly competitive business environment, consumers possess increasingly high quality standards and diverse choices, leaving companies with no room for compromise regarding product quality (Kazakov & Valijonov, 2021). A systematic approach to identifying, measuring, and reducing production defects has become a necessity for any manufacturing organization wishing to survive and thrive.

The Six Sigma method has emerged as one of the most influential quality management approaches in recent decades. Developed by Motorola in the 1980s and subsequently popularized by General Electric, Six Sigma offers a structured and data-driven framework for continuous quality improvement. The foundational philosophy of Six Sigma is to reduce variation in production processes so as to yield consistent products that meet specified standards (Obiako, 2025). A Six Sigma performance level is equivalent to 3.4 defects per one million opportunities, representing an exceptionally high standard of excellence in manufacturing. This methodology combines advanced statistical tools with a disciplined project management approach through the DMAIC cycle (Define, Measure, Analyze, Improve, Control) to identify the root causes of quality problems and implement sustainable solutions. Structured quality management approaches such as Total Quality Management have likewise proven capable of building product quality while strengthening the company's ability to maintain such excellence over the long term (Putra et al., 2017). The strength of Six Sigma lies in its capability to transform seemingly complex quality problems into issues that can be solved systematically.

The engineering statistics approach that forms the core of Six Sigma provides a strong scientific foundation for decision-making in quality control. Unlike traditional quality approaches that are often reactive and based on intuition, Six Sigma emphasizes the use of data and statistical analysis to understand the behavior of production processes. Tools such as Statistical Process Control (SPC), Design of Experiments (DOE), and Failure Mode and Effects Analysis (FMEA) are used in an integrated manner to identify sources of variation and determine the most effective improvement steps (Chawla, 2024). The systematic utilization of knowledge and data within an organization can also become a source of competitive advantage, particularly for companies operating in the information technology sector that rely on data-driven analysis for decision-making (Darmawan, 2023). This data-driven approach reduces reliance on guesswork and untested assumptions, resulting in solutions that are more targeted and scientifically accountable. In practice, the application of engineering statistics enables quality engineers to distinguish between variation caused by common factors inherent in the process and variation caused by special causes that can be identified and eliminated.

The application of Six Sigma in product quality control has brought about a significant transformation in how companies manage quality. Companies adopting Six Sigma not only experience a decrease in product defect rates, but also an increase in operational efficiency, a reduction in production costs, and an increase in customer satisfaction (Gomes et al., 2022). Six Sigma has transformed organizational culture by instilling a data-oriented mindset, discipline in problem-solving, and a commitment to continuous improvement. Leadership that upholds ethical values plays an important role in shaping a positive and sustainable organizational culture, thereby supporting the consistent application of a data-driven mindset across all levels of the company (Mardikaningsih et al., 2022). Employees at all organizational levels are trained to use statistical tools and problem-solving methodologies, making analytical capability a part of the company's core competencies. Employee productivity in the digital era also needs to be measured by considering individual creativity and innovation capabilities rather than mere work output alone, so that statistical tool training can deliver a more tangible impact on corporate performance (Darmawan, 2023). The involvement of all employees in such training, including senior workers, is important to ensure that the implementation of digital technology within the organization proceeds evenly without leaving behind certain groups of workers (Darmawan, 2023). The success of Six Sigma across various industries, ranging from electronic manufacturing and automotive to financial services, has proven the flexibility and effectiveness of this methodology in improving quality across diverse types of organizations.

The problem that arises in the implementation of Six Sigma is the difficulty in identifying the root causes of production defects accurately and efficiently. Although Six Sigma provides a range of advanced statistical tools, its effective use requires a deep understanding of production processes and the ability to interpret analysis results correctly. Many organizations that have adopted Six Sigma still experience difficulties in identifying the true sources of variation, because they frequently get trapped in symptoms without being able to trace down to the fundamental causes (Galli, 2019). An adaptive project management approach is also needed in a dynamic business environment, as the ability to quickly adjust strategies can help quality teams trace the root causes of problems amidst the complexity of continuously changing processes (Darmawan, 2021). This inability causes the improvement efforts undertaken to become ineffective, because the applied solutions only address surface-level problems without eliminating their root causes. Furthermore, the complexity of modern production processes involving many interacting variables makes statistical analysis increasingly challenging. Inappropriate statistical approaches or the use of tools that do not match the characteristics of the problem can yield erroneous conclusions, which subsequently lead to wrong improvement decisions and resource waste.

Six Sigma frequently generates improvement recommendations that are technically valid, but face obstacles during implementation due to organizational factors such as resistance to change, lack of resources, or misalignment with the company's strategic priorities (Kumar, 2020). Formal agreements among parties within the organization likewise influence the success of improvement implementations, as commitments clearly set forth can reduce the misalignment between technical recommendations and corporate strategic priorities (Da Silva et al., 2022). Moreover, the sustainability of quality improvements is often neglected, where achieved improvements do not last long due to the lack of effective control mechanisms. Research regarding rule enforcement in other sectors also demonstrates that firm and consistent control mechanisms play a major role in ensuring that an achieved improvement does not revert to its initial condition (Martono et al., 2025). Companies also face challenges in integrating the Six Sigma approach with existing quality management systems, resulting in effort duplication or methodological conflicts that reduce overall effectiveness. Responsible business governance also serves as a determining factor in ensuring that quality improvement recommendations are genuinely executed rather than remaining unacted-upon technical documents (Batubara et al., 2024). This gap between analysis and implementation becomes a major obstacle in realizing the full benefits of Six Sigma adoption, because quality improvement requires not only technical understanding but also the ability to manage organizational change effectively.

The complexity of production processes in the Industry 4.0 era has increased significantly with the presence of automation, connectivity, and interconnected cyber-physical systems. This technological development opens up great opportunities to improve product quality, but also creates new challenges in quality control because the interactions between variables become increasingly complicated and non-linear (Escobar et al., 2024). A culture of innovation capable of balancing the speed of technological development with human-centric considerations becomes important so that the implementation of automation and cyber-physical systems continues to pay attention to wise decision-making aspects (Darmawan, 2023). The Six Sigma method with an engineering statistics approach offers a framework that can adapt to this complexity, owing to its capability to analyze large amounts of data and identify patterns that are invisible through conventional methods. The application of circular economy principles in the industrial sector demonstrates that the utilization of data and technology can likewise be directed to support sustainable resource management, an objective that is also relevant to the efficiency brought by the Industry 4.0 era (Mardikaningsih & Nuraini, 2022). The relevance of Six Sigma continues to increase along with the availability of abundant production data from sensors and real-time monitoring systems, which can be utilized for more precise and responsive quality improvement. Thus, understanding the application of Six Sigma in product quality control becomes crucial to maximizing the potential of Industry 4.0 technology in enhancing the quality and competitiveness of manufacturing companies.

Changing consumer expectations regarding product quality also serve as an important driver for the study of this topic. Today's consumers not only demand products that function according to specifications, but also consistency in quality from one unit to another, as well as product reliability over a long period of use (Tekcan & Kirisken, 2010). Product development processes tailored to market needs likewise constitute a key to answering continuously changing consumer expectations, meaning that quality enhancement needs to be addressed starting from the product design stage rather than merely at the production stage (Sinambela & Aprilianti, 2012). Failure to meet these quality expectations can result in the loss of customer loyalty and the rapid, widespread dissemination of negative reviews through social media, which can damage a company's reputation quickly. In responding to these demands, companies need to possess a quality control system that is not only reactive to defects that have already occurred, but also proactive in preventing defects from arising before products reach consumers. Six Sigma with an engineering statistics approach provides the capability to predict and prevent rather than merely detect and correct, enabling companies to maintain consistently high quality standards and build long-term trust with their customers.

This literature review aims to systematically examine the application of the Six Sigma method with an engineering statistics approach in product quality control. Specifically, this research seeks to describe and analyze how statistical tools within the Six Sigma framework, such as Statistical Process Control, Design of Experiments, and Failure Mode and Effects Analysis, are utilized to identify production defect patterns, determine their root causes, and design effective improvement interventions. Furthermore, this study aims to explore how Six Sigma implementation can integrate statistical analysis into the broader corporate quality management system, including aspects of standard operating procedures, employee training, and a culture of continuous improvement. The theoretical contribution of this research is to enrich the understanding of Six Sigma working mechanisms in quality control, particularly in the digital era and Industry 4.0. The practical contribution is to provide literature-based guidance for quality management practitioners and production engineers in implementing Six Sigma more effectively, as well as identifying the critical success factors determining its implementation across various types of manufacturing industries.

Method

This research is a qualitative systematic literature review, aiming to conduct a thematic synthesis of key concepts and empirical findings regarding the application of the Six Sigma method with an engineering statistics approach in product quality control. The qualitative approach was chosen because it is highly suited to exploring the complexity of meaning, interpretive processes, and social construction inherent in the implementation of Six Sigma across various organizations. As explained by Makateng and Mokala (2025) in their review of qualitative research methodology, an understanding of the fundamental principles of qualitative research is essential for researchers to design credible and meaningful studies. The thematic synthesis method systematically developed by Braun and Clarke (2006) serves as the primary guideline in the process of identifying, analyzing, and reporting patterns of meaning emerging from the collected academic texts being examined. This approach enables the extraction of coherent insights from diverse sources to answer the formulated research questions.

The literature search strategy was conducted systematically to ensure comprehensive and relevant coverage. Primary searches were performed on leading academic databases such as JSTOR, Sage Journals, ScienceDirect, Scopus, and Google Scholar. Main inclusion criteria encompassed peer-reviewed journal articles, books, and conference proceedings that explicitly discuss the application of Six Sigma or engineering statistics tools in manufacturing product quality control. Works purely focused on managerial aspects without technical-statistical dimensions, or qualitative analyses without empirical data, were excluded from this review. The analysis process began with initial coding of the selected texts, which were then grouped into broader candidate themes based on their similarities and conceptual relationships, following the approach introduced by Brailas (2025). To ensure the quality and credibility of the analysis, this research implemented an audit trail by documenting all decisions made throughout the selection, coding, and theme development processes, as well as conducting triangulation of theoretical data sources from various disciplines such as industrial engineering, operations management, and applied statistics.

Result and Discussion

Identification and Analysis of Production Defects Using the Six Sigma Method

The Six Sigma method provides a structured framework for identifying production defects through a systematic engineering statistics approach. The Define phase in the DMAIC cycle serves as the initial foundation where quality problems are defined clearly and measurably, including the determination of product specifications, identification of critical quality characteristics, and establishment of realistic improvement targets. At this stage, the Six Sigma project team collaborates with stakeholders to understand the voice of the customer and translate customer needs into measurable technical requirements (Huang et al., 2022). Teamwork at this stage will run better if supported by an authentic leadership style, because a positive work climate makes team members more open in expressing their views and demonstrating work behaviors that go beyond formal duties (Mardikaningsih et al., 2022). Clarity in problem definition largely determines the success of subsequent stages, because without a proper understanding of what constitutes a defect and how to measure it, improvement efforts will lose direction and effectiveness. The define phase also encompasses value stream mapping and the identification of key processes that contribute to final product quality.

The Measure phase in Six Sigma focuses on the collection of accurate and representative data to understand current process performance. At this stage, statistical tools such as Statistical Process Control (SPC) and capability analysis are used to measure process variation and determine the extent to which a process is capable of meeting established specifications. Precise measurement requires a valid and reliable measurement system, which is frequently verified through Gauge Repeatability and Reproducibility (R&R) studies to ensure that the measured variation truly reflects process variation, rather than variation from measuring instruments or operators (Soliński & Soliński, 2021). The aspect of validity becomes non-negotiable in the data collection process, because invalid data will weaken the foundation of considerations built upon it, as emphasized similarly regarding the importance of ensuring the validity of a process so that it can serve as a basis for decision-making (Sulaiman et al., 2023). The data collected at this stage serves as the basis for further analysis, making data quality highly determinant of the accuracy of conclusions to be drawn. Without good data, any statistical analysis will yield misleading conclusions and ineffective recommendations.

The Analyze phase constitutes the core of the engineering statistics approach in Six Sigma, where collected data is analyzed to identify the root causes of production defects. At this stage, various statistical tools such as cause-and-effect diagrams, regression analysis, and Design of Experiments (DOE) are utilized to explore the relationship between process input and output variables. Regression analysis enables the team to identify which factors exert the most significant influence on product quality, while DOE allows for systematic testing of interactions between variables that might remain undetected through one-factor-at-a-time analysis. Careful statistical approaches enable the team to distinguish between truly significant causes and random variations that do not require corrective action (Dar et al., 2024). The ability to identify root causes accurately is key to designing effective solutions and avoiding the waste of resources on improvements that lack significant impact.

Statistical tools within Six Sigma not only assist in defect identification but also provide valuable predictive capabilities. Through time series analysis and statistical modeling, project teams can predict the likelihood of future defects based on historical data and observed trends. This predictive capability enables companies to take preventive actions before defects actually occur, transforming the quality control approach from reactive to proactive (Chawla, 2024). This proactive approach is highly valuable in reducing the cost of quality, as prevention costs are far lower than failure costs, which encompass rework, scrap, and customer loss. Capital readiness, the education level of human resources, and technology mastery also determine the extent to which these preventive actions can be consistently implemented, as these three factors have been shown to contribute to general business revenue growth (Sinambela et al., 2021). Thus, statistical analysis in Six Sigma serves a dual function: as a diagnostic tool to understand the past and as a prognostic tool to anticipate the future.

The engineering statistics approach in Six Sigma also enables finer variation analysis through data stratification based on relevant groupings. For instance, defect data can be grouped by work shift, production machine, raw material batch, or operator to identify whether process variation is systematic or random. Analysis of variance (ANOVA) and other statistical hypothesis tests are employed to examine the significance of differences between groups, allowing the team to determine which factors genuinely affect product quality. Such data stratification frequently reveals patterns that remain invisible when data is analyzed in aggregate, because variations caused by specific factors can mask one another when combined (Pakdil, 2020). When stratification is performed based on operators, differences in workforce backgrounds also need to be scrutinized, as the implementation of technology in tasks can exert varying effects on individual groups of workers, thereby influencing data grouping results (Darmawan, 2024). The ability to break down variation into its components is one of the primary strengths of the statistical approach in quality control.

The use of Failure Mode and Effects Analysis (FMEA) within the Six Sigma framework provides a qualitative dimension that complements quantitative statistical analysis. FMEA allows teams to systematically identify all potential failure modes that could occur in a production process, assessing the severity, occurrence, and detection ratings of each failure mode. The outcome of FMEA is the Risk Priority Number (RPN), which assists teams in prioritizing which failure modes must be addressed first based on their risk levels. The integration of FMEA and statistical analysis creates a comprehensive approach to defect identification, where quantitative analysis provides evidence of what is happening, while FMEA provides understanding of how and why failures can occur. This combination sharpens analytical precision and reduces the risk of overlooking potential sources of defects.

Challenges in defect identification using statistical methods frequently arise from the underlying assumptions of the statistical tools employed. Many statistical tools assume data normality, observation independence, and variance homogeneity, which may not always be fulfilled in real production data. Violations of these assumptions can yield biased conclusions if not handled appropriately. A sound understanding of statistical theory and the ability to diagnose assumption violations constitute essential skills for Six Sigma practitioners (Turkoz et al., 2019). The thoroughness in diagnosing such assumption violations is also influenced by the practitioner's working conditions, as changing work patterns, including the shift toward remote work, can impact psychological well-being and social relationships in the workplace, which ultimately affect the quality of analytical rigor (Darmawan, 2023). In practice, data transformation or the use of non-parametric statistical methods is often required to address assumption violations. The ability to select the appropriate statistical tool for the characteristics of the data at hand is one of the differentiating factors between successful and less successful Six Sigma implementations.

The interpretation of statistical analysis results in Six Sigma requires caution to avoid common errors such as mistaking correlation for causality. A statistical relationship between two variables does not necessarily mean that one variable causes changes in the other, as there may be an unobserved third variable influencing both. Furthermore, statistical significance does not always equate to practical significance; a factor may be statistically significant, but its impact on product quality is so minor that undertaking corrective action is not worthwhile (Allen, 2019). Six Sigma practitioners need to consider both statistical significance and practical significance in determining improvement priorities. An understanding of effect sizes and confidence intervals assists in assessing whether statistical findings possess meaningful practical implications for production operations.

The use of statistical software in Six Sigma has facilitated complex data analysis and enabled better visualization of analytical results. Software such as Minitab, JMP, and R provides interfaces that allow users to perform advanced statistical analyses without requiring deep mathematical understanding of the underlying theory. However, this convenience also carries its own risks, as users can generate statistical outputs without truly understanding what they are doing or how to interpret the results correctly. Adequate training in the use of statistical software and the interpretation of its results constitutes a vital component of Six Sigma implementation programs (Alagić, 2021). Employee readiness in utilizing these new software tools also depends on each individual's self-efficacy regarding their ability to adapt to technological changes, making the enhancement of self-efficacy an aspect that requires attention within training programs (Mardikaningsih & Darmawan, 2022). Strategies for increasing knowledge and employee engagement in automated jobs are likewise relevant to apply here, as more engaged users tend to be more capable of maximizing statistical software utilization rather than merely executing commands without comprehension (Darmawan, 2024). Companies that succeed in Six Sigma are those that balance the utilization of technology with the development of their employees' analytical competencies.

The best-known Six Sigma performance measures are Defects Per Million Opportunities (DPMO) and the corresponding sigma level, which provide a single metric to evaluate process quality performance. This metric allows for performance comparisons between different processes within the same organization or across different organizations. However, focusing solely on this single metric can also lead to oversimplification if not balanced with a more nuanced understanding of the process scope and the company's strategic priorities. Such strategic priorities are frequently shaped by prevailing regulations applicable to the business world, requiring companies to carefully monitor ongoing rules so that established quality targets remain aligned with the obligations and fairness applicable to business actors (Siswanto et al., 2024). DPMO and sigma levels are useful measures but should not become the sole focus in quality improvement efforts. True quality improvement requires an understanding of the entire production system and the impact of changes on various stakeholders, rather than merely achieving specific target numbers.

The statistical approach in defect identification must also consider the economic aspects of quality improvement. Not all defects carry the same consequences, and the cost of reducing defects to an extremely low level may not be proportional to the benefits gained. Careful cost-benefit analysis is necessary to determine the economically optimal quality level, where the cost of additional improvements begins to exceed the benefits of defect reduction (Blanco-Encomienda et al., 2025). The calculation of these improvement costs is ideally structured in the form of a detailed budget plan from the outset, much like the importance of preparing a mature cost budget plan before undertaking a task so that every expenditure can be accounted for and its benefits measured (Surbakti et al., 2023). Six Sigma provides tools for this economic analysis through the calculation of the cost of poor quality (COPQ) and return on investment (ROI) from improvement projects. The availability of financing also determines the extent to which quality improvement projects can be realized, making access to business funding sources necessary to manage carefully to avoid deviations from the intended empowerment objectives (Wicaksono et al., 2026). Furthermore, regulations governing digital-based financing need to be observed so that every quality improvement investment decision remains within the corridor of prevailing laws and financial markets (Yuristiawan et al., 2024). This economic-based approach ensures that company resources are allocated efficiently for quality improvements that deliver the greatest value to the organization.

Through the structured DMAIC cycle and the utilization of various statistical tools, Six Sigma enables organizations to transition from a reactive approach to a proactive approach in quality control. The primary strength of Six Sigma lies in its capability to integrate quantitative analysis with qualitative understanding of processes, resulting in more accurate root cause identification and more effective improvement solutions. The success of Six Sigma implementation heavily depends on the combination of technical competence in statistics, understanding of production processes, and organizational commitment to continuous improvement. With the right approach, Six Sigma can become an exceptionally effective instrument for enhancing product quality and company competitiveness in the global market.

Improvement of the Quality Management System through the Implementation of Six Sigma

The implementation of Six Sigma brings about a fundamental transformation in a company's quality management system, extending beyond mere product defect reduction toward comprehensive process improvement. A case study conducted by Smętkowska and Mrugalska (2018) in manufacturing production processes demonstrates that the systematic implementation of the DMAIC methodology is capable of identifying previously undetected sources of variation and yielding measurable continuous improvements. The improvements achieved are not limited to a decrease in defect rates, but also encompass increased operational efficiency, reduced production cycle times, and optimized resource utilization. Consistent product quality is also reflected in the packaging and visual identity used by the company, as product appearance serves as an indicator and signal of quality in the eyes of consumers (Sinambela & Aprilianti, 2013). The protection of brands, copyrights, and product designs also forms an important part of efforts to safeguard the value of quality that has been built, particularly for small and medium-sized business actors who are vulnerable to imitation (Hidayat et al., 2024). These findings indicate that Six Sigma functions as a catalyst for overall quality management system improvement, because the data-driven and structured approach compels organizations to reevaluate the assumptions underlying their production processes and identify improvement opportunities that were previously overlooked. Thus, Six Sigma is not merely a collection of statistical tools, but a management philosophy that transforms how organizations perceive and manage quality.

The transformation of the quality management system through Six Sigma is also visible in the strengthening of organizational analytical capabilities and the development of employee competencies. Training in the Six Sigma methodology, ranging from Yellow Belt to Master Black Belt levels, creates a knowledge infrastructure that enables quality improvements to be carried out in a decentralized manner across all organizational levels. Cross-functional training has likewise proven capable of strengthening team collaboration in executing joint improvement projects, ensuring that the results of Six Sigma training do not stop at mere mastery of statistical tools (Fared & Darmawan, 2021). Employees trained in Six Sigma are not only capable of using statistical tools, but also develop a systematic and data-driven problem-solving mindset. This analytical capability distributed across the organization creates resilience and sustainability in quality improvement efforts, as improvements no longer depend on a small group of specialists but become a shared responsibility. Employee engagement and commitment to work tasks are also largely influenced by positive psychological factors, meaning that the reinforcement of this aspect helps determine how actively employees participate in quality improvement projects (Darmawan & Mardikaningsih, 2022). Research conducted by Thomas, Francis, Fisher, and Byard (2016) in an aerospace company demonstrates that the implementation of Lean Six Sigma results in a significant increase in employee engagement and ownership of quality, which represents a critical element in a mature quality management system.

The integration of Six Sigma with existing quality management systems, such as ISO 9001 or Total Quality Management (TQM), creates a synergy that strengthens the foundation of organizational quality. Six Sigma provides structured methodology and tools to achieve goals established within the quality management system, while the quality management system provides a policy and procedure framework supporting the sustainability of improvements achieved through Six Sigma. A flexible organizational structure also facilitates this integration process, as a company's ability to adapt to environmental dynamics will smooth out the unification of two distinct management systems (Darmawan & Mardikaningsih, 2023). The tendency of some business actors not to establish a formal legal entity can also become its own obstacle in this integration process, because standardized quality management systems generally require a clear and documented organizational structure (Hardyansah et al., 2024). This combination yields a more precise approach to quality management, where compliance with standards and continuous improvement run in parallel and mutually reinforce one another. Conventional business actors facing pressure from online-based business developments also require a similar adaptation strategy, namely adjusting old working systems to new market demands in order to continue surviving (Arifin et al., 2022). Organizations that successfully integrate Six Sigma with existing quality management systems report greater improvements in quality performance compared to organizations implementing both separately. Synchronization between Six Sigma and quality management systems also reduces duplication of effort and procedural conflicts frequently occurring when various improvement initiatives run independently.

The control dimension in the DMAIC cycle constitutes a key element ensuring the long-term sustainability of quality improvements. In the Control stage, new standard operating procedures are documented, stricter monitoring systems are implemented, and response plans for deviations are developed to prevent the return of corrected defect conditions. Negligence in executing agreed-upon arrangements or procedures can trigger consequences similar to breach of contract in business relationships, making the control stage necessary to incorporate clear mechanisms for handling such deviations (Anggoro et al., 2024). When such deviations spark disputes among parties involved in the production process, resolution mechanisms through arbitration or mediation can serve as a more efficient exit compared to lengthy formal legal processes (Junaidi et al., 2024). Without effective control, improvements achieved through the Improve stage can quickly erode over time due to factors such as employee turnover, supplier changes, or equipment wear. The Control stage is frequently considered the most critical phase in ensuring that investment in Six Sigma projects delivers long-term value to the organization. Strict document verification and validation systems, as seen in the enforcement of identity rules and credit guarantees, demonstrate that administrative certainty forms an important part of a reliable control system (Handayani et al., 2025). Best practices in the Control stage encompass the development of real-time performance dashboards, routine audits of procedural compliance, and feedback mechanisms enabling early detection of quality deviations. Success in maintaining improvements frequently serves as the differentiator between organizations succeeding in Six Sigma and those experiencing only temporary improvements.

A case study conducted by Costa, Silva, and Ferreira (2017) on the extrusion process in tire production demonstrates how Six Sigma can overcome complex quality challenges through a meticulous statistical approach. This research identified that variations in extrusion temperature and raw material feed rate are the primary causes of product defects, which were subsequently resolved through process parameter optimization using Design of Experiments. The implementation of sustainable supply chain principles in similar manufacturing industries also shows that process parameter optimization can go hand in hand with improvements in operational performance and corporate social responsibility (Barzani et al., 2022). The success of this project not only improved product quality but also yielded significant cost savings through the reduction of scrap and rework. Improvements in such production processes also need to pay attention to the division of liabilities and consumer protection in product distribution agreements, so that the benefits of quality improvements truly reach the recipients of the final product (Kurniawan et al., 2024). These findings confirm that Six Sigma is effective in addressing multi-factorial quality issues, where interactions among process variables create complexities that cannot be resolved through conventional trial-and-error approaches. The engineering statistics approach enables the efficient identification of optimal process parameter combinations, reducing the time and cost required to achieve meaningful quality improvements.

Adeodu, Kanakana-Katumba, and Rendani (2021) in their research on the implementation of Lean Six Sigma in a paper company demonstrate that this approach is effective in optimizing production processes through the simultaneous reduction of waste and variation. The combination of Lean principles focused on waste elimination and the Six Sigma methodology focused on variation reduction creates a more comprehensive approach to quality improvement. Large-scale improvement projects of this nature also need to consider social responsibilities toward communities surrounding the production site, particularly when investments made have the potential to affect the lives of nearby residents (Aryanto et al., 2024). Lean Six Sigma enables organizations to address both operational efficiency and product quality aspects in an integrated manner, yielding greater improvements than the implementation of each approach separately. Such process improvement efforts become more meaningful when communicated to consumers through marketing approaches that highlight environmental commitment, thereby building consumer awareness regarding product quality and sustainability (Essa & Mardikaningsih, 2021). The findings of this research indicate that the implementation of Lean Six Sigma results in simultaneous, significant increases in productivity, quality, and customer satisfaction, which serve as strong indicators of the effectiveness of this integrated approach within modern quality management systems.

Byrne, McDermott, and Noonan (2021) in their case study at a pharmaceutical manufacturing facility demonstrate that Lean Six Sigma can be applied effectively in industries characterized by strict regulations and exceptionally high quality requirements. The pharmaceutical industry faces unique challenges in Six Sigma implementation due to stringent compliance requirements and extensive documentation, which are frequently regarded as obstacles to rapid process improvement (Pawar et al., 2025). Such compliance challenges are also visible in other sectors possessing specific certification requirements, such as the halal certification obligation for small and medium-sized business actors which similarly demands adjustments to production processes to remain compliant with applicable provisions (Hakiky et al., 2023). Anti-money laundering regulations in digital-based business sectors exhibit a similar pattern, where compliance with legal provisions must be fulfilled without sacrificing corporate operational smoothness (Fiana et al., 2024). However, this research demonstrates that Six Sigma can be adapted to meet regulated industry requirements while continuing to deliver significant improvement results. The protection of small-scale business actors amidst increasingly complex digital competition regulations further emphasizes that legal compliance and business competitiveness need to run hand in hand, much like quality compliance and process efficiency within strictly regulated industries (Firdaus & Hardyansah, 2025). The key to success in regulated industries is the meticulous integration of the Six Sigma methodology with existing quality management systems and compliance procedures, allowing improvements to be achieved without compromising regulatory compliance. These findings broaden the understanding of Six Sigma's flexibility and its capability to adapt to various distinct industry scopes.

Cabrita, Domingues, and Requeijo (2016) in their research on the implementation of Lean Six Sigma in a Portuguese bolt manufacturing company demonstrate that this methodology is effective in reducing production costs through waste reduction and quality improvement. This research identified that inefficiencies in production processes, such as long setup times, high material scrap, and recurring rework, were primary contributors to high production costs. Through the implementation of Lean Six Sigma, the company successfully reduced setup times by up to 30%, decreased the scrap rate by 25%, and eliminated almost all needs for rework. This significant cost reduction not only increased company profitability but also enhanced its competitiveness in a competitive market. This increased competitiveness needs to be maintained so that it is not abused into monopolistic practices that harm other small and medium-sized business actors in the same market (Indarto et al., 2023). Business partnership relationships, such as in franchisor and franchisee patterns, also indicate that the ethical foundation in cooperative working relations influences the resulting business performance, just as process efficiency influences production outcomes in this study (Putra et al., 2022). The findings of this research underscore that Six Sigma is not only beneficial for quality improvement but also possesses a direct and measurable financial impact, which strengthens the business case for investment in quality improvement initiatives.

The success of Six Sigma implementation heavily depends on the commitment and involvement of top management. Without support from the highest level of the organization, Six Sigma projects frequently encounter obstacles regarding resource allocation, change authorization, and the development of a sustainable improvement culture. The form of ownership and corporate structure further determine the extent to which management can make decisions rapidly, as different ownership structures carry different consequences of responsibilities and risks for business owners (Akbar et al., 2024). Top management plays a role in establishing strategic visions for quality, allocating adequate resources for training and projects, and removing organizational barriers that hinder improvement implementation (Pakdil, 2020a). The authority held by company leaders in making such strategic decisions is also inherent to the legal responsibility of corporate management, making commitment to quality also a part of broader managerial responsibilities (Nugroho et al., 2024). Top management involvement also sends a strong signal to the entire organization about the importance of quality as a strategic priority, which subsequently motivates employees at all levels to participate actively in improvement efforts. Such commitment is also tested when companies face regulatory uncertainty, wherein business sustainability strategies need to be structured so that managerial challenges do not impede the consistency of established quality standard implementation (Mardikaningsih & Darmawan, 2021). Organizations most successful in Six Sigma are those possessing leadership that consistently demonstrates commitment to quality and actively engages in improvement initiatives. Top management support frequently serves as the determining factor between the long-term success and failure of Six Sigma implementation.

An organizational culture that supports continuous improvement constitutes an essential prerequisite for the successful implementation of Six Sigma. Six Sigma requires an environment where employees feel safe reporting quality problems, where failures are viewed as opportunities to learn rather than as mistakes to be punished, and where improvements are valued as worthwhile contributions. Ethical values embedded within the organizational culture also function as an instrument for constructive internal conflict resolution, allowing differences of opinion in the quality improvement process to be resolved without damaging working relationships among team members (Khayru et al., 2021). Changing an established organizational culture is frequently a greater challenge than the technical aspects of Six Sigma implementation, because it involves changes in values, attitudes, and behaviors that have been ingrained within the organization for years (Leonard, 2020). The reinforcement of moral values and legal compliance in managerial decision-making practices also forms part of efforts to build a healthy organizational culture, as ethical decisions tend to be more easily accepted and adhered to by all members of the organization (Halizah et al., 2024). Effective law enforcement in preventing corrupt practices in business and investment activities also reflects an organizational culture of integrity, a condition that aligns with a work environment supporting honest and open problem reporting (Saputra et al., 2021). The cultural change process requires time, patience, and consistency from leadership in reinforcing values that support quality improvement. Organizations that successfully change their culture report that the benefits of Six Sigma are more enduring and broader than mere technical quality improvement, encompassing increased employee morale, cross-functional collaboration, and greater innovation.

Performance measurement in Six Sigma transcends traditional quality metrics by introducing a more balanced and comprehensive approach. Beyond Defects Per Million Opportunities (DPMO), organizations mature in Six Sigma also measure aspects such as the cost of quality, customer satisfaction, productivity, and employee engagement to obtain a more complete picture of their quality management system's performance. The management of large amounts of data also needs to be optimized to support managerial decision-making and the formulation of business strategies more precisely, in line with Six Sigma's need for accurate and comprehensive data (Ali & Darmawan, 2023). This balanced measurement approach prevents an excessively narrow focus on a single metric that could neglect other vital aspects of organizational performance (Krenek & Cho, 2015). Furthermore, an integrated measurement system enables organizations to track causal relationships between process improvements and overall business outcomes, reinforcing the justification for further investment in quality initiatives. Organizations that adopt a balanced measurement approach report being more capable of communicating the value of Six Sigma to stakeholders and maintaining support for long-term improvement initiatives.

The sustainability of improvement results in Six Sigma requires continuous monitoring and evaluation mechanisms. Companies successful in Six Sigma build systems that enable them to routinely review process performance, identify deviations early on, and take corrective actions before problems escalate. This ability to recognize risks early aligns with the importance of risk mitigation in investment activities, where early risk identification helps involved parties take preventive steps before larger losses occur (Sahid et al., 2023). This monitoring system frequently includes visual dashboards displaying key metrics in real time, allowing managers and operators to immediately see when processes begin to deviate from expected performance (AlMarzooqi, 2022). Furthermore, periodic reviews of completed Six Sigma projects help organizations identify additional improvement opportunities and ensure that achieved improvements persist. Ethical principles in business decision-making also need to be maintained throughout this monitoring process, as the company's sustainability and good relations with external stakeholders are likewise determined by the consistency of ethical values held by the organization (Mardikaningsih & Darmawan, 2022). Effective monitoring mechanisms transform Six Sigma from a one-time improvement project into a cycle of continuous improvement that becomes an integral part of the organization's daily operations. This sustainability is ultimately what differentiates organizations truly oriented toward quality from those undertaking only momentary improvements.

With the right approach, Six Sigma can become a powerful tool to transform a company's quality management system and create sustainable competitive advantage. The integration of statistical analysis, process understanding, and change management is the key to realizing the full potential of Six Sigma in improving quality management systems appropriately.

Conclusion

The Six Sigma method with an engineering statistics approach constitutes an effective and structured framework for product quality control across various manufacturing industries. Through the systematic DMAIC cycle, Six Sigma enables organizations to identify production defects accurately using statistical tools such as Statistical Process Control, Design of Experiments, and Failure Mode and Effects Analysis, which facilitate precise root cause analysis and effective improvement solutions. The implementation of Six Sigma also brings about a significant transformation in the company's quality management system, encompassing the strengthening of employees' analytical capabilities, the development of a culture of continuous improvement, integration with existing quality management systems, and the establishment of control mechanisms that ensure the sustainability of improvements. The success of Six Sigma implementation heavily depends on top management commitment, organizational culture readiness, technical competence in statistics and understanding of production processes, as well as the ability to manage organizational change. Case studies from various industries demonstrate that Six Sigma yields measurable improvements in product quality, operational efficiency, and reduction of production costs, which subsequently enhances the company's competitiveness in the global market.

For practitioners and operations managers, the findings of this review emphasize that Six Sigma is not merely a collection of statistical tools, but rather a management philosophy that requires long-term commitment and organizational culture change to achieve sustainable results. Successful implementation requires investment in employee training at all levels, ranging from basic statistical understanding to the ability to lead complex improvement projects. For academics and researchers, this study identifies existing research gaps, including the need for longitudinal studies tracking the long-term sustainability of improvements, as well as research exploring the adaptation of Six Sigma across different industries. For policymakers and industry associations, the implication of this research is the necessity to encourage the adoption of data-driven approaches in quality management through certification programs, industry standards, and incentives for companies that implement superior quality management practices.

Organizations intending to implement Six Sigma are advised to start with pilot projects in areas possessing high strategic impact, building initial success to gain support and momentum before expanding implementation across the entire organization. Collaboration between academics and practitioners needs to be enhanced to bridge the gap between theory and practice in Six Sigma implementation.

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