



**EXPLORING THE MODERATING ROLE OF
ARTIFICIAL INTELLIGENCE ON THE IMPACT
OF QUALITY MANAGEMENT ON
CONSTRUCTION PROJECT OUTCOMES**

(A Case Study of Jeddah Stormwater Program)

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List of Abbreviation

AI	Artificial Intelligence
AR	Augmented reality
BIM	Building Information Modelling
CQM	Construction Quality Management
CV	Computer Vision
FMEA	Failure Mode and Effects Analysis
IoT	Internet of Things
ITP	Inspection Testing Plans
JSWP	Jeddah Stormwater Program
ML	Machine Learning
MIR	Material Inspection Request
MOS	Method of Statements
NCR	Non-Conformance Report
NLP	Natural Language Processing
PDCA	Plan Do Check Act
PMO	Project Management Office
PQP	Project Quality Plan
QA	Quality Assurance
QC	Quality Control
QI	Quality Improvement
QMS	Quality Management Systems
SOR	Site Observation Reports
SPC	Statistical Process Control
TQC	Total Quality Control
TQM	Total Quality Management

Chapter Two

Review of Literature

Overview

Construction Quality Management has emerged as a vital and indispensable factor in determining the success and overall performance of construction projects. CQM is a critical component that significantly contributes to achieving project goals, meeting clients' requirements, and satisfying their expectations. It encompasses a range of processes and procedures that ensure construction projects are delivered to the specified standards and quality levels, ultimately leading to enhanced customer satisfaction and the organization's ability to differentiate itself from competitors in the highly competitive construction industry.

As Zhang et al. (2014) explained, organizations are often driven to implement quality management systems either by a rational motivation—seeking to improve internal performance and project outcomes—or by a social motivation, aiming to conform to external expectations and gain legitimacy. Understanding these underlying drivers is essential for evaluating the effectiveness of CQM practices in achieving tangible project success.

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Mega construction projects, including infrastructures, have widely acknowledged CQM as a crucial factor in enhancing project outcomes. However, the successful implementation of quality management in construction projects is not without its challenges. Understanding the relationship between Construction Quality Management and various project outcomes is crucial (Bittharia, 2021). While construction quality management practices such as quality assurance and control have been shown to significantly contribute to project success, their application can also present unique challenges that require careful navigation, especially in the absence of proper quality planning. This chapter will explore the complexities of effectively applying quality management principles within the construction industry and examine how these practices can influence key project performance metrics, including budget, schedule, quality, and customer satisfaction (Teshome & Gobana, 2018).

Understanding the challenges of implementing CQM practices in construction and infrastructure projects, and how these practices impact project outcomes, lays the foundation for incorporating emerging technologies like artificial intelligence to optimize and enhance

quality management effectiveness in the construction industry (Hamdan, 2024). AI tools and techniques, such as automating quality processes, identifying and predicting quality issues, can help address the complexities of implementing effective CQM practices. AI-driven solutions can automate and streamline quality control, enable real-time monitoring and data analysis, and provide predictive insights to proactively mitigate quality-related issues. By leveraging AI, construction firms can improve the efficiency and effectiveness of their quality management practices, leading to better project outcomes in terms of cost, schedule, quality, and customer satisfaction (Regona et al., 2023).

The recent advancements in AI and digital technologies have already started to transform CQM practices. According to Luo et al. (2022) these emerging technologies can improve defect detection, compliance monitoring, and quality control efficiency. In their study, AI-driven solutions such as Building Information Modeling (BIM), Augmented Reality (AR), Internet of Things (IoT) and Computer Vision (CV) have been integrated into the quality management framework. The results were enhanced pre-construction defect prevention, reducing rework and ensuring adherence to quality standards. By leveraging AI in CQM, projects can minimize human errors, accelerate quality inspections, and enhance customer satisfaction, making it a critical tool that can leverage large-scale infrastructure projects to tackle the challenges associated with the complexities of these projects, where traditional CQM practices cannot fully address.

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Theoretical Foundations of Construction Quality Management

It is crucial to understand the theoretical foundations and principles of Construction Quality for developing a comprehensive approach to quality management in construction. CQM is rooted in the theoretical principles and frameworks established by quality management pioneers such as W. Edwards Deming, Joseph Juran, Crosby, and Armand Feigenbaum. Deming's philosophy emphasizes process control, statistical quality management, and the Plan-Do-Check-Act (PDCA) cycle, which has become a fundamental aspect of international quality standards like ISO 9001 (Neyestani, 2016). Juran's Quality Trilogy—quality planning, control, and improvement—has been instrumental in structuring quality processes in construction projects, ensuring that project outcomes align with client expectations and regulatory standards (Juran & Joseph, 2012). Meanwhile, Crosby's "Zero Defects" concept underscores the importance of a defect-prevention mindset, reducing rework and improving

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cost efficiency in large-scale projects (Crosby, 1980). These foundational concepts provide a strong theoretical basis for understanding the key elements and best practices of quality management, which have been adapted and applied to the unique context of the construction industry.

The research conducted by Neyestani, B. (2016) highlighted the effectiveness of QMS, particularly ISO 9001, in enhancing project performance across the construction industry. The study conducted in Metro Manila found that implementing robust QMS, that is adhering to strong theoretical background such as ISO 9001, had the most significant impact on customer satisfaction, followed by cost and time efficiency, with low impact on project scope. The result of this study aligns with the importance of the foundational theories of CQM, where there is a need for strong proactive planning, continuous improvement, and systematic quality control contribute to better project outcomes, especially in large scale projects.

Building on Neyestani's findings, recent empirical studies conducted in Saudi Arabia further reinforce the critical role of QMS in the construction sector. For example, Aichouni et al. (2014) examined the readiness and implementation of QMS among contractors in the Hail region and found that while awareness of ISO 9001 and TQM existed, the actual application of quality tools and practices was limited. The study highlighted that only 44% of surveyed companies had a formal ISO 9001 system, and less than half employed a quality manager, indicating a fragmented quality culture. Similarly, Abdul Hakim and Mat Naim (2006) emphasized that although many construction organizations pursue ISO 9000 certification, misunderstanding of Project Quality Plans (PQP) and a compliance-focused mindset often undermine the full realization of customer satisfaction and project performance. These findings suggest that despite the global recognition of ISO-based QMS frameworks, effective implementation in the Saudi construction context requires stronger organizational commitment, better training, and integrated project-level quality planning.

Recognizing the inherent complexities and challenges faced by construction projects, the integration of well-established quality management theories—such as those of Deming, Juran, and Crosby, provide a solid framework for effectively implementing CQM practices and addressing the specific quality-related issues that arise in the construction domain. As evidenced by empirical studies within the Saudi construction industry, however, the successful application of these principles requires not only technical knowledge but also organizational

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commitment, capacity building, and context-sensitive adaptation. By grounding CQM in well-established quality management theories, construction firms can develop a more robust and systematic approach to enhance quality performance, reduce rework, and consistently meet client and stakeholder expectations, thereby ensuring the successful delivery of construction projects that meet or exceed the specified standards, requirements, and customer expectations.

Quality Management Frameworks

The ISO 9000 series

The ISO 9000 series is a set of internationally recognized standards developed by the International Organization for Standardization (ISO) to establish QMS across industries, including construction. The most widely implemented standard in this series is ISO 9001, which provides a framework for organizations to ensure consistent quality, process efficiency, and customer satisfaction. These standards emphasize a process-driven approach to quality management, focusing on continuous improvement, risk-based thinking, and compliance with regulatory requirements. In construction projects, ISO 9001 certification is often required by clients and regulatory bodies to demonstrate an organization's commitment to quality assurance and compliance with industry best practices (Neyestani, 2016).

ISO 9001 (2015) standard outlines seven key quality management principles that are critical in the construction industry:

1. Customer Focus – Meeting and exceeding client expectations in project execution.
2. Leadership – Ensuring quality objectives align with the organization's vision.
3. Engagement of People – Empowering employees at all levels to contribute to quality.
4. Process Approach – Managing construction activities through well-defined processes.
5. Continuous Improvement – Continually enhancing construction practices and methodologies.
6. Evidence-Based Decision Making – Using data & audits to drive quality improvements.
7. Relationship Management – Strengthening collaboration with suppliers, subcontractors, and stakeholders.

Implementing ISO 9001 in construction projects requires several important steps, including establishing a documented quality management system, conducting internal and external audits, implementing corrective actions, and continuously monitoring performance metrics. Many construction firms adopt ISO 9001-certified quality systems to streamline document

control, material inspections, and compliance procedures, thereby reducing rework costs, project delays, and contract disputes. For large-scale infrastructure projects, such as stormwater networks or highway construction, ISO 9001 provides a standardized framework for managing quality across multiple contractors, subcontractors, and suppliers, ensuring consistency and reliability.

A case study conducted by Hamdan, M. (2024) on the construction of a 22-kilometer stormwater network in the UAE highlights the importance of strict quality assurance procedures in achieving project success. The study found that rigorous material testing, site inspections, and adherence to documented quality protocols were essential in preventing defects and ensuring compliance with client expectations. Another study by Khalfan et al. (2020) also supports this while investigating ISO 9001 certified construction industry and found that TQM practices—such as leadership involvement, employee training, supplier integration, and process control—serve as key drivers of operational performance. Their research underlined that projects with a strong quality culture and continuous improvement mechanisms are more likely to experience smooth transitions from execution to maintenance, minimizing rework and cost overruns. Together, these findings underscore how structured quality management systems, grounded in TQM principles, enhance the durability and efficiency of large-scale infrastructure projects.

Another study on Malaysian construction projects conducted by Mukhtar et. al. (2010) revealed that ISO 9001-certified contractors experienced fewer non-conformance reports (NCRs), lower material wastage, and reduced rework costs, leading to better project performance and financial savings. The research emphasized that one of the core aspects of ISO 9001 is its focus on performance measurement and continuous improvement, which is particularly relevant for large-scale infrastructure projects. The quality cost approach—which includes prevention, appraisal, and failure costs—was identified as a crucial tool for assessing and improving construction quality performance. However, the study also noted that knowledge gaps among project teams often limit the full potential of ISO 9001, highlighting the need for better training and awareness programs to enhance its effectiveness.

Implementing ISO 9001 Quality Management and ISO 14001 Environmental Management have significantly contributed to the operational success of DB Construction, leading to a 34% annual growth. According to BSI (2011), the integration of these management systems helped the company enhance process efficiency, improve client satisfaction, and strengthen compliance with regulatory requirements. Adopting structured quality management practices

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by DB Construction helped the company to reduce inefficiencies, streamline documentation, and improve overall project performance, demonstrating the value of internationally recognized quality standards in the construction industry.

These examples reinforce how ISO 9001-based QMS frameworks enhance efficiency, reduce costly rework, improve stakeholders' satisfaction and contribute to the overall durability of infrastructure projects. In large-scale infrastructure projects like JSWP, ISO 9001 is critical, as it involves multiple stakeholders, complex materials supply chains, and stringent regulations and client needs, requiring a structured quality management system to ensure compliance, minimize defects, and improve efficiency. Contractors are required to fully adopt ISO 9001 and align their QMS with JSWP's standards, as it plays a vital role in ensuring quality consistency and enhancing project efficiency. Integrating JSWP's quality requirements into a comprehensive Quality Manual, contractors can standardize their Inspection and Test Plans and Method Statements, fostering proactive defect prevention, better stakeholder coordination, and smoother project execution.

However, contractors often implement QMS either to align with strategic project goals or to meet regulatory, industry, or project requirements. Zhang et al. (2014) distinguished between the rational perspective, where quality systems are strategically adopted to improve performance, and the social perspective, where they view ISO 9001 as a bureaucratic formality, focusing on passing audits rather than improving quality on-site, which is the case for some contractors in JSWP. In such cases, Quality Manuals are generic, developed only for certification or approval purposes, leading to inconsistent quality control, task delays, and frequent revisions. Another study from Jordan's construction industry revealed that many ISO-certified firms had employees unaware of the standard's actual significance, reflecting poor implementation and weak integration into daily activities. This reactive approach results in higher defect rates, increased rework costs, and misalignment with quality objectives, ultimately delaying project progress and increasing contractual disputes (Hiyassat, 2000). Such disparities in ISO 9001 adoption are evident within JSWP, which highlights that the true value of a QMS lies in its meaningful implementation, not just its certification.

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Total Quality Management (TQM)

TQM is a comprehensive quality approach that focuses on continuous improvement, customer satisfaction, and proactive defect prevention throughout a project's lifecycle. In the construction industry, TQM principles help ensure that quality is embedded at every stage, from planning, design to execution and project handover. Which is not like the traditional quality control methods, that focus on defect detection after occurrence. TQM emphasizes preventive strategies, such as process optimization, employee engagement, and data-driven decision-making.

Several major construction firms have successfully implemented TQM to enhance project outcomes. For example, Bechtel Corporation, a globally recognized engineering and construction company, adopted TQM methodologies and Six Sigma principles to improve processes, reduce construction defects, and minimize the cost of defects and rework. By integrating structured quality control procedures into daily site operations, Bechtel's quality improvement initiatives resulted in \$200 million in savings, following an initial investment of \$30 million in a defect prevention and process optimization program (Oguz et al., 2012). This case highlights how TQM-driven quality management strategies can lead to significant cost reductions and improved project efficiency in large-scale construction projects.

In Saudi Arabia, the implementation of TQM is increasingly recognized as a key strategy for enhancing project performance and competitiveness in the construction sector. While global frameworks such as ISO 9001 have provided structured foundations for quality systems, their real impact lies in how effectively TQM principles are embedded within project execution. A study by Mazher, Gharlegghi, and Fah (2015) investigated four key TQM dimensions—quality management, quality control, quality assurance, and quality inspection—within Saudi construction firms, finding that the first three had a statistically significant positive impact on project quality. Notably, quality management showed the strongest correlation, emphasizing the importance of strategic planning, leadership commitment, and systematic process management. These findings complement those of other studies in the region, which suggest that employee engagement, continuous improvement, and integrated quality frameworks are essential to achieving project success.

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For large-scale infrastructure programs like JSWP, these insights affirm that TQM and ISO 9001 must go beyond documentation and compliance to become a fully embedded organizational culture, throughout the projects lifecycles, enabling better coordination, reduced defects, and enhanced client satisfaction. The implementation of TQM in large-scale infrastructure projects in Saudi Arabia, such as the Riyadh Metro, has faced challenges. While TQM provided strict quality planning, assurance, and continuous monitoring that can minimize construction errors in some cases, there have also been reports of quality-related issues and major delays. Contractors may have struggled to fully integrate TQM principles into their daily operations, leading to inconsistent quality control and a disconnect between the intended benefits and the actual project outcomes (Abazid, 2017).

While TQM is widely recognized for its benefits in construction, it is not formally implemented in JSWP, as ISO 9001 is followed as its quality management framework. However, the core principles of TQM—continuous improvement, defect prevention, and process optimization—are inherently embedded within ISO 9001 requirements. Contractors working under JSWP are expected to apply ISO 9001-driven quality management processes, such as structured ITP, MOS, and Material Inspection Requests (MIRs) to maintain compliance and ensure consistency across all projects. The effectiveness of ISO 9001 still depends on how well contractors integrate quality practices into their daily operations rather than treating compliance as a procedural obligation.

To summarize, the construction industry's adoption of structured quality management systems, such as ISO 9001 and TQM, has demonstrated significant benefits in enhancing project outcomes, reducing defects, and improving overall efficiency. These frameworks provide a systematic approach to managing quality across the project lifecycle and have been widely embraced in both global and regional contexts. Within the Jeddah Stormwater Program, ISO 9001 serves as the primary quality framework, offering a standardized structure for quality manuals, ITPs, and MOS, but the meaningful implementation of its principles is crucial for realizing its full potential in improving construction quality, cost, and schedule performance.

The Quality Gurus

Juran's Quality Trilogy in Construction

Juran's Quality Trilogy, developed by the pioneer quality management expert Dr. Joseph Juran, is a foundational framework in the field of quality management. This model consists of three interrelated processes: Quality Planning, Quality Control, and Quality Improvement. The Quality Trilogy emphasizes a proactive approach to quality management, ensuring that defects and inefficiencies are minimized through structured planning, continuous monitoring, and data-driven improvement (Juran & Joseph, 2012).

In the context of construction projects, Juran's Quality Trilogy can serve as a comprehensive quality management strategy. Juran's principles are widely applied to enhance project execution, cost efficiency, and long-term infrastructure reliability. By integrating these three quality management processes, construction firms can systematically plan for quality, actively control and monitor quality-related activities, and continuously improve their quality management practices. This comprehensive approach helps construction organizations achieve their desired project outcomes, meet or exceed customer expectations, and deliver high-quality infrastructure that stands the test of time.

Juran's Quality Trilogy has been recognized for its effectiveness in reducing waste, minimizing rework, and improving overall project performance in construction. Some argue that its rigid framework may not always be well-suited for the dynamic, complex, and changing nature of construction projects. The one-fit approach of the Quality Trilogy may fail to accommodate the unique challenges and constraints faced at each project, leading to suboptimal implementation and limited impact on project outcomes. Moreover, the extensive planning and documentation required can be seen as bureaucratic, unnecessary and time-consuming, as seen on JSWP contractors, potentially hindering the agility and responsiveness needed to adapt to changing project conditions.

Although JSWP primarily adopts the ISO 9001 quality management framework as a contractual requirement, the core elements of Juran's Quality Trilogy are inherently aligned with the structured approach of ISO 9001. Contractors working under JSWP must engage in comprehensive quality planning through detailed manuals, quality control via Inspection and Test Plans and rigorous inspections, and quality improvement through continuous audits and

corrective actions. Effective integration of these complementary principles through ISO 9001, JSWP contractors can foster a proactive quality management mindset, and rather than merely reactive compliance when ISO is only a formality that needs to be done. This approach can help reduce defects, optimize processes, and ultimately improve overall project outcomes.

Deming's PDCA Cycle in Construction

Deming's Plan-Do-Check-Act (PDCA) Cycle is a widely used continuous improvement model that emphasizes an iterative approach to quality management. Initially developed by Dr. W. Edwards Deming, the PDCA cycle ensures that quality is managed proactively rather than reactively, making it particularly valuable in construction projects where deviations from standards can lead to significant cost overruns, delays, safety risks, and reduced customer satisfaction. The cycle consists of four key stages as shown in figure 2 below.

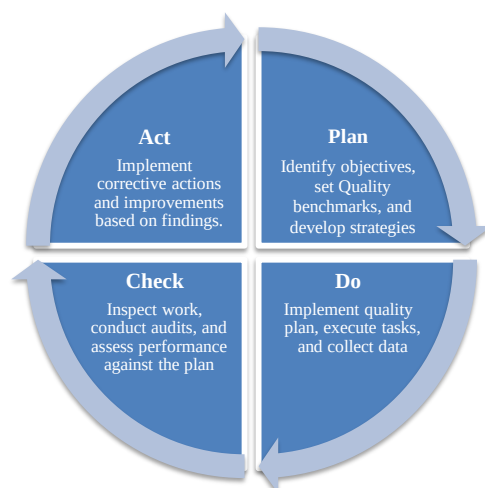


Figure 02: Deming Cycle PDCA

Applications of PDAC in Construction

The PDCA cycle is widely applied in construction to ensure proactive quality management, prevent defects, and drive continuous improvement. In the Cross-rail Project (London's Elizabeth Line), the Plan phase was used extensively to define quality benchmarks, conduct risk assessments, and develop quality control strategies, preventing material failures and

structural weaknesses before construction began (Project and Program Management, 2023). Check phase played a crucial role in the Hong Kong-Zhuhai-Macao Bridge project, where frequent inspections and real-time monitoring were used to detect early signs of structural stress and ensure compliance with engineering standards, reducing post-construction defects (Zhu et al., 2018). The act phase was used in the Riyadh Metro project, where lessons from early construction phases led to better material selection, workflow efficiency, and safety improvements, minimizing rework and enhancing overall project quality (Abazid, 2017). These examples demonstrate how the PDCA cycle systematically integrates planning, monitoring, and corrective actions to improve project outcomes, reduce defects, and optimize construction processes.

The author sees the PDCA cycle as an important model in large infrastructure projects as it creates a continuous feedback loop that enables consultants and contractors to identify and address quality issues at every stage of the project lifecycle. Within the Jeddah Stormwater Program, the application of Deming's PDCA cycle is evident in the structured quality management system required by the ISO 9001 framework, this model can help in integrating lessons learned from finished projects into new projects, especially during the planning stage, to incorporate lessons learned into the packages before reaching the bidding stage.

Crosby's "Zero Defects" Philosophy in Construction

Philip Crosby's "Zero Defects" philosophy is a quality management approach that emphasizes doing things right the first time (DRIFT) to eliminate defects, reduce rework, and enhance project efficiency. Unlike traditional quality models that focus on detecting and correcting errors after they occur, Crosby's methodology promotes a preventive mindset, as quality is built into processes rather than inspected at execution stage (Crosby, 1980). This principle is relevant in large-scale construction projects, where issues in materials, workmanship, or execution can lead to significant cost overruns, delays, and safety issues.

Application in Construction

Crosby's "Zero Defects" philosophy has been successfully applied in various high-profile infrastructure projects, presenting its effectiveness in enhancing quality control and reducing rework. The implementation of strict quality planning, supplier compliance audits, and defect-prevention strategies has helped minimize construction errors and material defects, ensuring

that the work meets stringent regulatory and safety standards (Salvi & Kerkar, 2020). This approach, which focuses on doing things right the first time, has been instrumental in improving the long-term performance of construction projects by eliminating material inconsistencies and structural defects.

While the ISO 9001 framework is the primary quality management system in JSWP, Crosby's principles are already embedded in the program's quality approach. Contractors are required to establish comprehensive Quality Manuals, ITPs, and MOSs to ensure quality is controlled at every stage of construction. The contractors who adhere to JSWP's quality standards, implement supplier audits, inspections, and defect-prevention strategies, are aligning with Crosby's "Zero Defects" philosophy. However, when no planning is in place, Crosby's zero-defect approach may not be effective. This highlights the importance of integrating both the PDCA cycle and Crosby's principles into the quality management system to drive continuous improvement and eliminate defects throughout the construction lifecycle (Hwang & Yang, 2014) (Alinizzi et al., 2020).

Conclusion and Proposed Solution

Construction Quality Management is a crucial aspect of large infrastructure projects, as it directly impacts project outcomes in terms of cost, schedule, quality, and customer satisfaction. The PDCA cycle and Crosby's "Zero Defects" philosophy provide effective frameworks for implementing a proactive and preventive quality management approach in the construction projects. Integrating these principles into the construction process can help construction project teams to identify and address quality issues, minimize defects. This will drive continuous improvement and enhance the overall performance leading to success of the project.

The Pyramid of Quality

The author developed the pyramid of quality integration to illustrate the evolution of quality thought and its structured application within the construction industry. Figure 03 illustrates the layered integration of quality management thinking into construction practices, showing how foundational theories have evolved into structured systems that drive modern project outcomes. At its foundation are the contributions of quality pioneers—Deming, Juran, and Crosby—who introduced key principles such as

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continuous improvement, process focus, and defect prevention. These theoretical contributions informed the rise of Total Quality Management in the 1980s, emphasizing organizational culture, leadership, and system-wide quality responsibility. Subsequently, the development of the ISO 9001 standard translated these principles into a formalized quality management framework, emphasizing process control, documentation, and continuous auditing. Within the construction sector, these standards were further operationalized through Construction Quality Management (CQM) practices, including Quality Management Systems, Inspection and Test Plans, Non-Conformance, and on-site inspections. At the top of the pyramid lie the intended results of these layered practices: project outcomes in terms of cost, time, quality, and customer satisfaction.

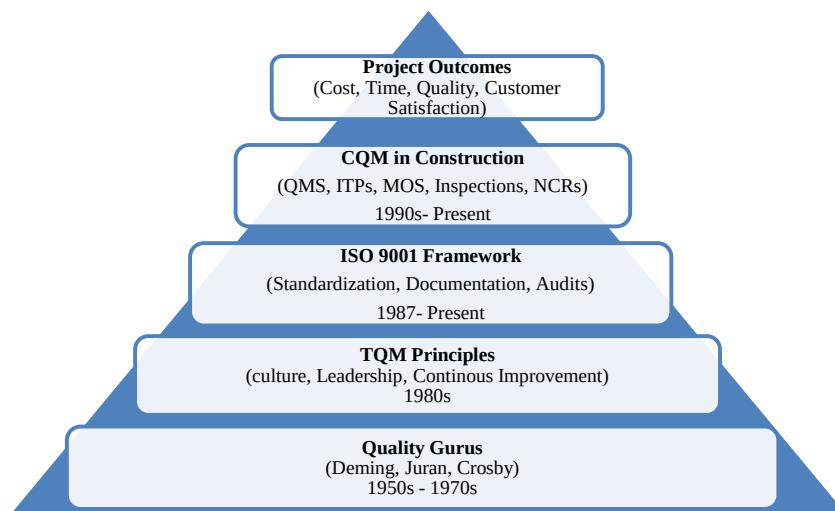


Figure 03: Pyramid of Quality Integration into Construction

How Iso 9001 Acts as integrative Framework

Elements of the discussed quality management theories and models are inherently implemented within JSWP as the program officially adheres to ISO 9001 as its primary quality management system, its implementation naturally integrates fundamental principles from the quality theories. Figure 04 illustrates how the foundational principles and concepts introduced by quality pioneers—Deming, Juran, and Crosby—have shaped the development

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of structured frameworks like TQM and ISO 9001, which form the theoretical backbone of modern quality systems. From Deming, ISO 9001 inherits the PDCA cycle, process orientation, and emphasis on continuous improvement. While Juran quality trilogy incorporates a structured approach to quality planning, control and improvements, Crosby, reflects the preventive approach over proactive inspections. ISO formalizes TQM's broader concepts—customer satisfaction, employee and mangement involvement, and system-wide quality responsibility—into documented procedures, measurable objectives, and audit processes.

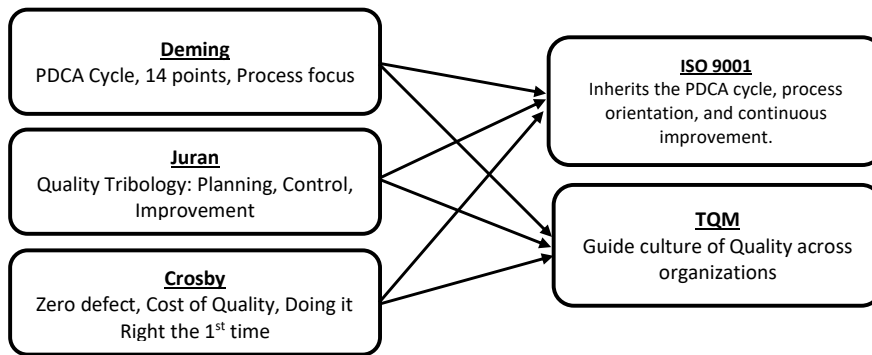


Figure 04: Contributions Of Quality Gurus To Modern Management Frameworks

Building on the previous discussion of figure 4, the overlapping principles of Deming, Juran, and Crosby highlight a shared foundation that underpins modern quality management systems. The Venn diagram on figure 05 below shows how Both Deming and Juran advocate for continuous improvement, while Crosby and Deming stress defect prevention over post-inspection correction. Juran and Crosby align on the need for structured planning and clear accountability in quality implementation. These overlapping principles not only reinforce the theoretical consistency behind modern frameworks like ISO 9001 and TQM but also justify their integration into Construction Quality Management (CQM) systems used in complex infrastructure projects such as the Jeddah Stormwater Program (JSWP). The interaction of All three emphasizes customer satisfaction, measurable performance, and organizational commitment to quality which are the core values of modern quality management frameworks

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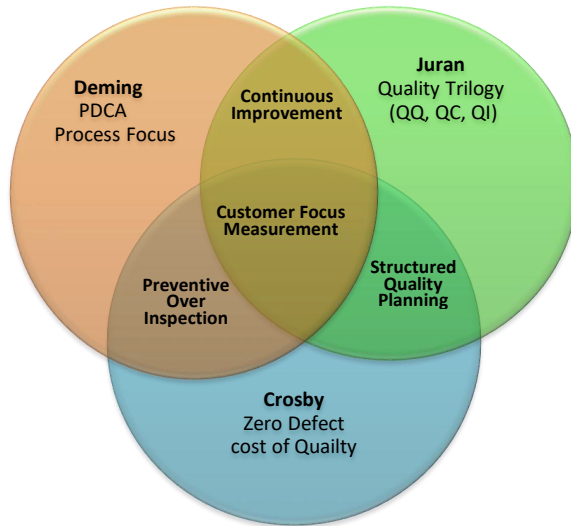


Figure 05: Overlapping Principles of Deming, Juran and Crosby

Proposed Solution

The success of JSWP's quality efforts ultimately depends on how contractors and stakeholders apply these principles in practice through a combined framework. Therefore, quality management in JSWP is not defined by a single theory but rather by a hybrid approach that combines the best practices from various models, tailored to the program's specific needs and challenges. In this sense, ISO 9001 functions as a key player that bridges theory and practice, offering a structured pathway for implementing CQM across diverse construction environments, including complex multi-stakeholder programs like JSWP.

With the increased size and complexity of projects challenges persist. The lack of top management commitment, inadequate training, and the implementation of ISO 9001 requirements as a bureaucratic obligation often results in a weak and inconsistent implementation of the quality management system. To address these challenges, construction companies involved in JSWP, and similar large-scale infrastructure programs should prioritize executive-level engagement in quality planning and monitoring. At the operational or execution level, quality initiatives for site engineers, supervisors, and quality personnel are

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essential to bridge the gap between policy and execution. In addition, the integration of digital quality management tools, such as automated submittal workflows, mobile inspection platforms, and real-time dashboards, can help standardize compliance processes and improve transparency across contractors and subcontractors.

Furthermore, the adoption of AI technology in CQM presents a transformative opportunity to help overcoming challenges of existing QMS, and to move from reactive to predictive quality management. AI-powered tools, including computer vision for defect detection, machine learning algorithms for quality risk prediction, and natural language processing for document review—can significantly reduce inspection time, identify patterns in non-conformances, and enhance decision-making accuracy. Embedding AI into quality workflows can help construction companies optimize inspection and testing practices and align quality performance with broader project and company objectives. These intelligent systems, when combined with human oversight and leadership commitment, offer a strong strategy for enhancing CQM practices and ensuring that quality becomes a measurable, data-informed driver of project success in JSWP and beyond.

Construction Quality Management

Construction Quality Management is a comprehensive approach incorporating a wide range of practices and processes designed to ensure delivery of construction projects. The goal is to meet or exceed the specified standards, requirements, and customer expectations by implementing various quality control and assurance measures throughout the project lifecycle. The aim is to optimize project outcomes and enhance customer satisfaction.

Quality in construction is about adherence to appropriately established standards and specifications. It is a management approach that ensures the construction process is completed within the specified quality requirements, on time, within budget, safely, and meeting customer expectations. CQM involves systematically organizing and coordinating various processes, including planning, implementing, and monitoring quality-related activities to achieve the desired outcomes. (Teshome & Gobana, 2018).

According to the influential quality management scholars Juran and Godfrey, Construction Quality Management involves the comprehensive coordination and integration of all quality

assurance and quality control activities throughout the entire project lifecycle. Juran and Godfrey (Juran & Joseph, 2012) emphasize that CQM is not merely about inspections and checklists, but rather a proactive, end-to-end management system that aligns all quality-related processes and procedures to ensure the successful delivery of the construction project. Adopting this quality management approach is essential for achieving the project's objectives and meeting the specified requirements and standards.

The author highlights that effective CQM requires a strategic, systematic, and collaborative approach from all key project stakeholders, including owners, contractors, subcontractors, and designers, to work towards achieving the desired project outcomes. This comprehensive and integrated approach is crucial for ensuring that quality-related activities and processes are aligned with the overall project objectives and coordinated throughout the project lifecycle. By actively engaging all stakeholders and fostering a shared commitment to quality, CQM can optimize project performance in terms of cost, schedule, quality, and customer satisfaction. On the other hand, if construction firms do not adopt this comprehensive approach, it can lead to significant challenges and suboptimal project outcomes, such as the following examples listed by Low & Ong (2014):

- Increased project costs due to the need for rework, waste, and inefficiencies
- Delays in project schedules from quality-related issues and errors
- Compromised quality of the final product or infrastructure
- Reduced project life cycle and sustainability of the project
- Dissatisfied customers and a damaged reputation for the construction firm

Therefore, the effective implementation of a robust CQM system is essential for construction firms to achieve their desired project outcomes and meet the expectations of their clients and stakeholders. To achieve that, the industry must address the key challenges associated with CQM implementation and explore innovative solutions to optimize its effectiveness, such as integrating emerging technologies and artificial intelligence.

Construction Quality Management Dimensions

Establishing and implementing an effective Construction Quality Management system necessitates a comprehensive understanding of the key components and fundamental principles that underpin successful construction quality management practices. Building into Juran's Trilogy Construction Quality Management will be divided into four critical

dimensions that ensure project success: Quality Planning, Quality Control, Quality Assurance, and Quality Improvement. Each of these dimensions plays a vital role in maintaining compliance with standards, minimizing defects, improving efficiency, and enhancing project outcomes (cost, schedule, quality, and customer satisfaction). In large infrastructure projects, these dimensions contribute to the effectiveness of the quality management system, ensuring that construction activities adhere to regulatory, contractual, and performance requirements.

Quality Planning

Quality Planning is the core of Construction Quality Management, it serves as a proactive strategy by defining quality objectives, standards, and procedures before construction begins. It help in establishing all project requirements, including materials, workmanship, safety, and compliance with regulations, in advance. Effective Quality Planning helps to prevent defects, minimize rework, and align project execution with stakeholder expectations, ultimately contributing to cost efficiency, schedule adherence, and improved overall project outcomes (Juran & Joseph, 2012).

One component of Quality Planning is establishing clear quality objectives based on contract specifications, engineering standards, and regulatory codes, such as the Saudi Building Code and ISO 9001 guidelines. These objectives define the minimum acceptable standards for construction activities, to ensure that materials, processes, and workmanship meet the predefined requirements. For example, in metro rail projects, strict adherence to track alignment, concrete strength, and vibration resistance is a core quality objective to maintain long-term structural integrity.

Another component of Quality Planning is identifying potential risks and developing mitigation strategies. This includes conducting risk assessments to detect quality failures, material inconsistencies, and execution errors before they escalate. For instance, during the Palm Jumeirah project in Dubai, early identification of soil settlement risks led to the use of enhanced compaction techniques and real-time monitoring, ensuring the stability of the artificial islands (Higgins, 2013).

Another vital part of Quality Planning is developing ITPs and MOSs to ensure that construction activities are executed correctly. These documents outline inspection frequency, acceptance criteria, and corrective measures, serving as essential tools for maintaining

compliance with quality standards. A good example is the Hong Kong-Zhuhai-Macao Bridge project, where rigorous concrete durability and steel reinforcement testing protocols were implemented, preventing premature material degradation (Zhu et al., 2018). Additionally, proper documentation and compliance management are integral to Quality Planning. Maintaining traceable records of quality inspections, material certifications, and work approvals is crucial for regulatory compliance, particularly in ISO 9001-certified projects.

Quality Control

Quality Control (QC) in construction is the systematic process of monitoring, inspecting, and verifying construction activities to ensure compliance with project specifications, regulatory requirements, and contractual obligations. Unlike Quality Planning, which focuses on pre-construction strategies, Quality Control is done during construction to detect defects, deviations, and non-conformities in real-time. Effective QC practices minimize rework, reduce project delays, and enhance overall structural integrity, ultimately improving project outcomes in terms of cost, schedule, quality, and customer satisfaction.

A fundamental aspect of Quality Control is conducting regular inspections and material testing to verify compliance with project specifications. This includes pre-construction material testing, in-process quality checks, and final inspections before project handover. For example, in the Hong Kong-Zhuhai-Macao Bridge project, engineers implemented real-time structural health monitoring and material testing to prevent premature degradation and ensure durability (Zhu et al., 2018). On the other hand, during the construction of the Riyadh Metro, comprehensive NDT protocols were applied to detect cracks, defects, and voids in concrete and steel structures, enabling timely corrective measures (Abazid, 2017).

Another key component of Quality Control is the use of ITPs and NCRs to document inspection procedures, acceptance criteria, and corrective actions for defects. ITPs ensure that all critical construction activities—such as reinforcement, waterproofing, and placement of concrete—undergo systematic quality verification before proceeding to the next stage. When non-conformities arise, NCRs help track deviations, analyze root causes, and implement corrective actions, ensuring that defects are addressed efficiently to prevent costly rework.

However, as highlighted in the stormwater network project case study (Hamdan, 2024), the lack of strict adherence to quality control measures such as ITPs and NCRs led to delayed defect identification and inefficient corrective actions. While QMS was in place, its inconsistent enforcement among contractors resulted in quality violations, increased rework, and project delays. The absence of proactive quality control procedures meant that defects in material storage, trench excavation, and reinforcement installation were often detected too late, causing costly rework and timeline disruptions. This case emphasizes the critical role of early intervention and strict quality monitoring in ensuring compliance with project specifications and minimizing inefficiencies (Hamdan, 2024).

Quality Control also includes the implementation of statistical process control techniques to monitor and improve the processes. Analyzing data from material testing, inspection results, and other quality metrics, can help construction firms to identify opportunities for process improvement, adjust procedures, and ensure consistent quality across multiple project sites. This process can be even enhanced using artificial intelligence technologies, which can help construction firms automate data analysis, predict quality issues, and optimize QC workflows.

In conclusion, Quality Control is an essential dimension of CQM that ensures compliance with project specifications, reduces defects, and enhances overall project reliability. In JSWP and other large-scale infrastructure projects, well-structured inspection and testing procedures, combined with effective defect management strategies, contribute to cost reduction, schedule efficiency, and long-term performance of constructed assets. However, the effectiveness of Quality Control depends on how consistently contractors implement and adhere to these processes, reinforcing the need for strict compliance with ISO 9001 and project-specific quality requirements.

Quality Assurance

Quality Assurance (QA) in construction is a proactive approach that focuses on preventing quality issues before they occur, in contrast to the reactive nature of Quality Control. QA is a preventive, process-oriented approach that ensures quality is built into every phase of the project lifecycle. Unlike QC, which focuses on detecting and correcting defects, QA emphasizes establishing standardized procedures, best practices, and compliance frameworks to prevent defects from occurring in the first place. QA ensures that contractors adhere to

project specifications, industry regulations, and contractual requirements, ultimately improving cost efficiency, schedule adherence, and long-term durability (Juran & Joseph, 2012).

A fundamental aspect of Quality Assurance is the establishment of a Quality Management System (QMS) that provides a framework for managing quality on the project. This includes developing Quality Manuals that document quality policies, procedures, and responsibilities to ensure that all stakeholders—contractors, consultants, and suppliers—follow consistent quality standards. Another key element of QA is the implementation of regular audits, management and compliance reviews to verify adherence to established quality procedures. These audits help identify gaps in quality processes, areas for improvement, and necessary corrective actions.

Quality Assurance (QA) includes the prequalification of suppliers and subcontractors to ensure that only high-quality materials and certified vendors are used in the projects. The process includes strict supplier evaluation and approval procedures, where all materials must be procured from approved sources as per tender documents, any changes in suppliers must be closely monitored. Patel et al. (2021) found that before implementing ISO 17020, poor supplier selection and inadequate material storage led to quality inconsistencies and defects.

However, with a structured quality assurance framework, projects saw significant improvements in material handling, supplier compliance, and adherence to quality standards. This proactive approach reduces the risk of structural defects, enhances construction durability, and ensures that materials meet regulatory and project-specific requirements.

Quality Assurance is a preventive approach that establishes systematic procedures and quality frameworks to maintain high construction standards throughout a project. In JSWP, the project management office consultant (PMO) plays an important role in ensuring consistency, supplier accountability, and minimizes defects and rework. Quality Control, led by the Supervision Consultant, focuses on identifying and correcting defects, QA ensures that quality failures are avoided from the start. However, the effectiveness of QA depends on how well contractors implement and adhere to these processes, and their strict compliance with ISO 9001 standards and project-specific quality requirements.

Quality Improvement

Quality Improvement (QI) in construction goes beyond the traditional approaches of Quality Control and Quality Assurance. QI in construction is a continuous process of analyzing project performance, identifying areas for enhancement, and implementing corrective actions to achieve higher efficiency, reduced defects, and better overall project outcomes. Unlike QA, which establishes preventive processes, and QC, which detects and corrects defects, Quality Improvement focuses on learning from past experiences and refining construction practices over time. By systematically improving quality standards, construction firms can minimize inefficiencies, lower rework costs, and optimize long-term project sustainability.

A key component of Quality Improvement is the use of lessons learned and post-project evaluations to refine construction practices. Many successful infrastructure projects, such as the London Cross rail project, implemented structured post-construction reviews to identify quality issues, assess material durability, and optimize design practices for future phases. By analyzing previous project deficiencies, construction firms can implement corrective actions and prevent recurring defects (Project and Program Management, 2023).

Another key component of Quality Improvement is the use of data analytics and performance measurement. Construction companies can leverage data from project management systems, quality control processes, and customer feedback to identify patterns, detect root causes of quality issues, and develop improvement strategies. For example, by analyzing inspection reports and defect logs, firms can pinpoint the most common types of quality failures, assess their impact on project outcomes, and implement corrective training, process changes, or technological solutions to address these recurrent problems (Abdullah et al., 2005).

Furthermore, Quality Improvement also emphasizes the importance of fostering a strong quality culture within construction organizations. Combined with training skill development programs, and continuous learning, this promotes a proactive mindset among project teams, empowering them to identify and address quality problems as they emerge. Well-trained workers and engineers are more likely to follow the best practices, identify quality risks early, and contribute to continuous process optimization (Naor et al., 2008).

Quality Improvement is a long-term approach that aims to refine construction processes, enhance defect prevention strategies, and adopt advanced quality techniques. In the JSWP project, this area requires major attention from all stakeholders. Lessons learned, technological advancements, and workforce training initiatives can play a crucial role in continuously improving project quality. Quality Assurance and Quality Control focus on maintaining predefined standards, Quality Improvement ensures that standards developed based on real-world project experiences. The effectiveness of Quality Improvement depends on an organization's commitment to innovation, proactive problem-solving, and adaptability to changing construction challenges.

Construction Quality Management, Project Outcomes, and AI

Quality management in construction is a critical aspect that can significantly impact project outcomes. The effectiveness of CQM is directly linked to the success of construction projects, which is commonly measured through four key project outcomes: cost, schedule, quality, and customer satisfaction. These project outcomes define the overall efficiency, performance, and success of a construction project. Also, it determines whether it meets its intended objectives and stakeholder requirements. Effective Construction Quality Management practices can contribute to optimizing these key project outcomes, leading to better financial performance, timely project delivery, high-quality construction, and enhanced customer satisfaction (Neyestani, 2016).

Cost - The financial aspects of project execution, including budgeting, controlling and minimizing cost overruns, and optimizing the efficiency of resource utilization to ensure the project is delivered within the planned budget constraints. Effective Construction Quality Management practices can contribute to cost savings by reducing waste, rework, and material defects, as well as improving productivity and resource allocation.

Schedule (Time) – The timely completion of construction activities according to milestones, deadlines, and schedule requirements is a critical outcome of construction quality management. It is critical to ensure that projects are delivered on time, meeting stakeholder expectations, maintaining cash flow, and avoiding penalties or reputational damage (Sota, 2017). Effective quality management practices, such as thorough planning, resource

allocation, and progress monitoring, can contribute to the successful and timely delivery of construction projects

Quality – The degree to which the construction project meets or exceeds the specified design requirements, regulatory standards, and durability expectations for the built infrastructure. This encompasses compliance with design drawings, construction codes and guidelines, as well as the long-term performance and reliability of the completed facility. Effective CQM practices aim to ensure that the final product achieves the desired level of quality, functionality, and service life in accordance with stakeholder requirements while exceeding their expectation (Teshome & Gobana, 2018).

Customer Satisfaction – The perception and level of fulfillment experienced by stakeholders, including clients, end-users, and regulatory bodies, the project's overall performance, functionality, and compliance with their expectations and requirements (Neyestani, 2016). This includes factors such as the final product meeting requirements, achieving the desired function and technical quality, and satisfying the needs and preferences of the end-users. Effective CQM practices can contribute to enhancing customer satisfaction by ensuring the constructed facility aligns with requirements and delivers the expected value and utility.

Incorporating these key project outcome measures can support construction organizations evaluate the impact of their CQM practices and make informed decisions to optimize project success. The following sections analyze the impact of CQM on each of these project outcomes, demonstrating how effective quality management practices contribute to improved project performance.

Impact of CQM on Project Cost

CQM plays a pivotal role in controlling and optimizing project costs. Proper planning, implementation, and control of quality management processes can lead to significant cost savings throughout the project lifecycle. Project costs in construction are affected by multiple factors, including material selection, labor efficiency, rework, delays, and contract variations. Poor quality management often leads to defective work, non-conformities, and cost overruns due to rework and wasted materials. Effective CQM practices, such as detailed Quality

Planning, proactive Quality Control, and continuous Quality Improvement, help minimize financial risks and optimize resource utilization.

Based on the study "Effectiveness of Quality Management System on Construction Projects" by Neyestani (2016), a real-world example highlighting the impact of QMS implementation on construction project performance is construction projects in Metro Manila, Philippines. The study found that strict quality management practices, including inspections, material testing, and supplier prequalification, significantly improved project outcomes. The data indicated that contractors who adhered to ISO 9001-based QMS experienced fewer defects, reduced rework, and lower project costs, reinforcing the necessity of a structured quality framework in construction projects (Neyestani, 2016).

Implementing strong CQM practices, such as clear quality objectives, rigorous planning, and strict quality assurance, aligns with Crosby's Zero Defects philosophy, which emphasizes preventing defects rather than fixing them. This approach is crucial for JSWP, thorough material testing for stormwater pipes and structural inspections for pumping stations can reduce costly rework and delays. Contractors who adhere to ISO 9001-based quality procedures experience fewer budget deviations, while those with poor quality management face financial penalties, increased labor costs, and extended timelines. A Zero Defects mindset ensures efficient project execution, cost control, and long-term infrastructure reliability.

Impact of CQM on Project Schedule

Schedule adherence is a critical factor in project success, as delays can lead to increased costs, contract disputes, and reputational damage. Poor quality management often results in non-conformities, defects, and rework, affecting the project timeline. Quality issues, such as design defects, substandard workmanship, and material non-conformities, can lead to significant project delays, rework, and extended construction timelines. The Big Dig project in Boston is a notable example of how poor-quality planning and material failures can lead to significant project delays and cost overruns. Initially estimated at \$2.8 billion with a completion date set for 1998, the project ultimately cost around \$22 billion and was completed eight years later than planned. Issues such as substandard materials and inadequate sealing of tunnels contributed to these setbacks (RICS, 2023).

In JSWP, contractors following structured ITPs and well-defined Quality Assurance procedures experience smoother project execution with fewer unexpected delays. Proactive quality monitoring and timely resolution of issues ensure that construction activities are completed as per the planned schedule, with minimizing the rework and enhancing overall project efficiency. When quality issues, such as defected materials, are identified early through systematic inspections and audits, corrective actions can be promptly implemented before the material is used, to avoid significant schedule disruptions.

Impact of CQM on Project Quality

Construction Quality Management is the primary driver for ensuring the desired level of quality in construction projects. Its goal is to ensure that construction projects meet predefined quality standards, durability requirements, and compliance with engineering codes. Effective Construction Quality Management practices, including quality planning, assurance, and control, are crucial for achieving and upholding the necessary quality standards throughout the project lifecycle. These practices can also mitigate the detrimental effects of poor-quality management, which may result in structural failures, safety risks, and long-term performance problems.

The study by Aichouni *et al.* (2014) on construction projects in Saudi Arabia found that the implementation of a robust quality management system, with a focus on quality control, had a significant positive impact on the overall quality of construction projects. The authors highlighted that the strict adherence to quality control measures, such as regular inspections, material testing, and monitoring of construction processes, led to a reduction in defects, improved workmanship, and enhanced customer satisfaction. Similarly, a case study on a stormwater network project in the UAE conducted by Hamdan (2024) emphasized the critical role of implementing Construction Quality Management practices to meet required standards and customer needs.

These studies align with the needs of JSWP, as quality can be achieved through strict compliance with QMS, especially ISO 9001 standards. The implementation of CQM practices, such as compliance with industry standards, product certifications, and regular third-party inspections, helps ensure the quality and durability of critical infrastructure components, such as water pipes, precast manholes, and marine outfalls. Contractors that

prioritize quality management ensure that their structures withstand environmental conditions, minimize maintenance costs, and function efficiently for decades.

Impact of CQM on Customer Satisfaction

Customer satisfaction in construction is not limited to end-users and project owners but also includes regulatory bodies, local authorities, and environmental agencies. Effective Construction Quality Management is a crucial factor in enhancing customer satisfaction in construction projects. A well-executed project that adheres to quality standards and meets deadlines, within budget, contributes to higher stakeholder confidence and client satisfaction.

Expo 2020 demonstrates that effective CQM is not just about building infrastructure but also ensuring that quality management enhances user satisfaction, safety, and sustainability. The clear planning, strict assurance measures, and continuous improvement strategies used in Expo 2020 reflect CQM principles, proving that well-managed construction quality leads to higher customer satisfaction. A survey conducted at Expo 2020 revealed that 95% of visitors to the Terra Pavilion pledged to adopt sustainable practices, demonstrating the impact of high-quality infrastructure and engaging experiences on public behavior. Additionally, the event's stringent health and safety protocols, including the "Dubai Assured" certification, ensured a safe experience for over 24 million visitors, further reinforcing how proactive quality management fosters trust, enhances user experience, and meets stakeholder expectations.

In the context of JSWP, the implementation of robust CQM practices—including regular site inspections, material testing, and quality audits—has played a crucial role in ensuring that infrastructure projects meet the expectations of local authorities, environmental agencies, and the public. However, quality issues and rework can contribute to project delays, leading to prolonged road closures and disruptions to daily life for citizens. Since the local community is a key stakeholder in JSWP, extended construction timelines can result in traffic congestion, accessibility challenges, and public dissatisfaction. While effective quality management practices aim to minimize such disruptions, unforeseen defects or inefficiencies may still delay project completion and impact residents. Therefore, contractors must carefully balance rigorous quality control with efficient project execution to mitigate inconveniences and uphold public confidence in large-scale infrastructure improvements.

AI as an enhancer of CQM

Advancements in digital technologies, particularly Artificial Intelligence (AI), are transforming traditional construction management practices. In the realm of Construction Quality Management (CQM), AI has emerged not as a substitute, but as a powerful enhancer that fortifies each core quality function. By integrating predictive analytics, real-time data processing, and intelligent automation into established quality systems, AI enables construction teams to shift from reactive issue handling to proactive quality assurance. This transformation is especially crucial in large-scale infrastructure projects, where complexity and fragmentation often challenge traditional quality control mechanisms. Table 01 below provides a summary of how AI technologies can enhance the four primary dimensions of CQM—Quality Planning, Quality Control, Quality Assurance, and Quality Improvement—by enhancing accuracy, efficacy, and decision-making capabilities across each function.

Table 01: AI Technology enhancement for current CQM practices

CQM Dimension	Current traditional Practice	AI enhancement
Quality Planning	Manual plans, Historical risk-based planning	Predictive analysis, BIM integrated modeling, AI integrated management software
Quality Control	Manual checklists, visual inspections, manual spreadsheets	Computer vision, drone inspection, sensors, Image recognition supported inspection applications
Quality Assurance	Periodic audits, site walkthroughs	Real time dashboards, anomaly detection, predictive analysis, triggers warnings
Quality Improvement	Post-completion lessons learned	AI prediction and patterns recognition, root cause analysis supported by AI

AI serves as a strategic enabler within CQM, enhancing the effectiveness of quality planning, control, assurance, and improvement practices. While traditional CQM frameworks rely heavily on manual inspections, scheduled audits, and document-driven processes, AI introduces capabilities such as real-time monitoring, predictive analytics, and intelligent automation. These technologies allow for proactive issue identification, faster decision-making, and continuous learning from project data. Rather than replacing established quality systems like ISO 9001 or TQM, AI enhances their implementation, making CQM more responsive, accurate, and integrated—especially in large-scale infrastructure projects like the Jeddah Stormwater Program (JSWP).

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Figure 06 is the updated Pyramid of quality, shows the integrated relationship between CQM practices, AI technologies, and project outcomes. Each core function of CQM—planning, control, assurance, and improvement—is enhanced by AI applications such as predictive analytics, real-time monitoring, and automated defect detection. The figure also showing how the AI enhanced CQM practices is predicted to improve the project outcomes, reflecting the hypothesis discussed in chapter 1. AI’s role is visualized not as an isolated tool but as a catalyst that strengthens the entire quality management ecosystem, enabling better performance across large-scale infrastructure projects like the Jeddah Stormwater Program (JSWP). Thus, working as a continuous enabler improving each layer — from planning and assurance to inspection and project outcomes, which is another representation of how the integrated theories of the quality gurus shaped ISO 9001 and TQM.

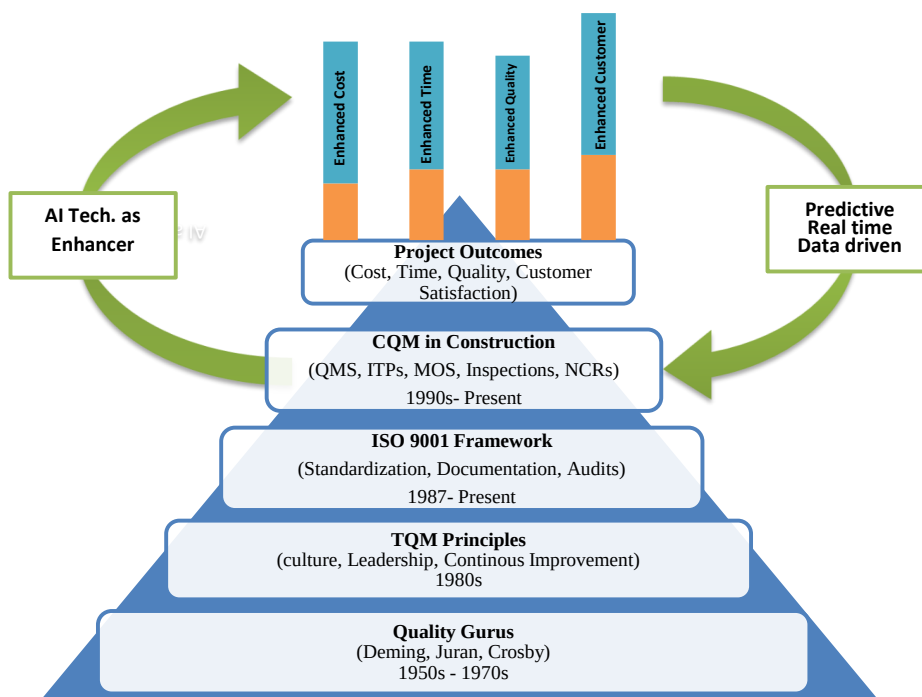


Figure 06: The Pyramid of Quality with integrated AI technology as an enhancer

Research Gaps and Conclusion of the Literature Review

The literature review has highlighted the significant impact of Construction Quality Management on the various aspects of project performance, including cost, schedule, quality, and customer satisfaction. Although the existing body of research provides valuable insights into the importance of CQM, the effectiveness of CQM systems becomes insufficient as the scale and complexity of projects increase. There is a need to further explore the potential of emerging technologies, such as Artificial Intelligence, to enhance the effectiveness of CQM practices and improve overall project outcomes.

Also, the reviewed literature suggests that AI-powered technologies, such as automated inspections, predictive analytics, and workflow optimization, can significantly improve the efficiency and accuracy of quality management processes. Furthermore, AI-enabled real-time monitoring and decision support systems can empower project teams to identify and mitigate quality issues proactively, reducing the risk of rework, delays, and cost overruns. However, those research often focuses on isolated applications of AI in quality management, without addressing its holistic, systematic impact on overall CQM practices and project performance.

Furthermore, extensive research has been conducted on CQM and its impact on project outcomes. Several gaps remain, particularly in the context of large-scale infrastructure projects like JSWP and the adoption of advanced quality management technologies. The key research gaps identified from literature include as illustrated on figure 03 below:

- **Limited Studies on CQM in Large-Scale Infrastructure Projects in Saudi Arabia:** While the existing literature provides a general understanding of CQM and its implications, there is a lack of research specifically focused on the challenges and best practices of implementing CQM in large-scale infrastructure projects within the Saudi Arabian context. Most of the existing studies on CQM have focused on residential, commercial, or small-scale construction projects, with limited research specifically addressing the challenges and best practices of CQM in large-scale infrastructure projects, particularly in the Saudi Arabian context. There is a lack of empirical data on how ISO 9001-based QMS frameworks perform in large infrastructure programs like JSWP and their effectiveness in mitigating quality risks, cost overruns, and schedule delays.
- **The Need for a Deeper Understanding of CQM's Direct Impact on Project Outcomes:** While studies confirm that quality management improves project performance, there is

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limited quantitative research on the degree of impact each dimension of CQM (Quality Planning, Quality Control, Quality Assurance, and Quality Improvement) has on cost, schedule, quality, and customer satisfaction. However, as the complexity and scale of projects increase, such as in JSWP, more in-depth analysis is needed to understand the relative importance and interrelationships between various CQM practices and their direct impact on project outcomes.

- **Challenges in Implementing ISO 9001 in Multi-Contractor Infrastructure Projects:** The literature highlights the challenges faced by construction firms in effectively implementing ISO 9001-based quality management systems, particularly in large, complex projects with multiple contractors and subcontractors. The lack of a unified, collaborative approach to quality management across the supply chain often leads to inefficiencies, inconsistencies, and quality issues.
- **Further research is needed to identify best practices and strategies for implementing robust CQM frameworks in multi-stakeholder infrastructure projects, especially in the context of the Saudi Arabian construction industry.** Although project requirements at JSWP strictly adopt ISO 9001, more investigation is needed to evaluate how ISO 9001 compliance is interpreted and applied differently by contractors and whether it is truly integrated into their daily quality processes or treated as a procedural requirement.
- **The Role of Emerging Technologies in Enhancing CQM Practices:** The existing literature often emphasizes the general advantages of AI in construction, such as its impact on a specific project outcome or its application to specific quality management issues. Studies acknowledge the potential of individual technologies like AI, BIM, and IoT to address specific quality management issues such as inspections, defect detection, and workflow optimization. There is a lack of empirical research on the systematic integration and holistic impact of these technologies on overall Construction Quality Management effectiveness and project performance. This research aims to provide a more comprehensive understanding of how emerging technologies can enhance the implementation and impact of quality management systems in large-scale infrastructure projects.

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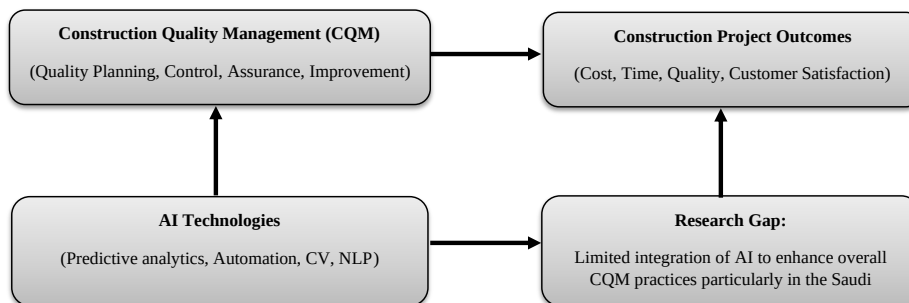


Figure 03: Gap in Literature – The Moderating Role of AI on the Relationship Between CQM and Project Outcomes

Recent exploratory research on the adoption of Artificial Intelligence in the Saudi construction industry provides valuable empirical support for the gaps identified in this literature review. In a targeted survey of 60 construction industry professionals, Ujaimi et al. (2024) confirmed several key barriers to AI implementation, including technical limitations, high costs, lack of skilled personnel, regulatory ambiguity, and resistance to change. These challenges reflect the limited digital readiness of many construction firms and expose the operational and organizational weaknesses in current CQM systems. The findings suggest that existing quality practices are often not strong enough to support or integrate advanced technologies, particularly in large-scale infrastructure projects involving multiple stakeholders, like those under JSWP.

This study thus functions as a pilot investigation, confirming not only the presence of barriers to AI adoption but also the underlying deficiencies in the implementation of systematic quality practices. By identifying these real-world challenges—such as the absence of standardized digital platforms, insufficient training on quality tools, and fragmented quality data—the research underscores the urgency of rethinking how CQM can be enhanced through technological integration. These insights validate the need for deeper academic inquiry into the moderating role of AI in strengthening CQM practices and improving project outcomes.

To address the identified gaps, a multi-layered approach is suggested to improve the implementation of Construction Quality Management in large-scale infrastructure projects. First, management-level engagement should be enhanced by incorporating quality objectives into strategic plans and performance evaluations. Second, training programs and workshops should be established to increase quality awareness and capability among project teams, particularly in ISO 9001 application and CQM tools such as ITPs and NCRs. Third, project

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owners should encourage the use of integrated digital platforms for real-time quality tracking, documentation, and inter-contractor coordination. This includes adopting AI-enabled tools for predictive defect detection, automated submittal reviews, and workflow optimization, which can improve the effectiveness and responsiveness of CQM practices across complex, multi-stakeholder environments like JSWP.

Despite growing interest in the application of AI in construction, existing research has yet to fully explore its role as a moderator between CQM practices and project outcomes. This opens an important research opportunity: understanding how AI integration into Quality Planning, Control, Assurance, and Improvement can elevate the efficiency and impact of CQM. This study aims to address this gap by examining the moderating effect of AI technologies on the relationship between CQM and project outcomes within the context of the Jeddah Stormwater Program. The next chapter will build on these findings by introducing a conceptual framework and research methodology designed to evaluate the interaction between AI technologies and quality management systems in the context of JSWP.

Conclusion of the Literature Review

This chapter has provided an extensive review of CQM and its impact on key project outcomes, focusing on Quality Planning, Quality Control, Quality Assurance, and Quality Improvement as the four core dimensions of CQM. The literature has demonstrated that effective quality management strategies lead to reduced cost overruns, fewer schedule delays, improved project durability, and higher stakeholder satisfaction. On the other hand, the literature highlighted several key barriers to the successful implementation of quality management in the construction industry, including issues with inconsistent application of quality practices, the inherent complexity and variability of construction work, and broader challenges within the industry itself.

The analysis also revealed that while CQM principles are well-established, their implementation varies significantly depending on contractor commitment, technological integration, and project-specific challenges. In the JSWP, ISO 9001-based quality management systems provide a structured approach to ensuring defect-free execution, but the effectiveness of these systems depends on how well contractors integrate them into their daily operations.

Despite the well-documented benefits of CQM in construction, several research gaps remain, particularly regarding its impact on infrastructure projects in Saudi Arabia, its role in reducing project risks, and the integration of advanced digital quality management tools. Addressing these gaps through empirical research will help refine the best practices, improve policy recommendations, and enhance the long-term effectiveness of quality management in large-scale infrastructure projects.

This literature review establishes the foundation for the next phase of the research, which will focus on analyzing how CQM dimensions influence project outcomes in JSWP and exploring ways to optimize quality management practices for improved performance.

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