

**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
MOS	Method of Statements
NCR	Non-Conformance Report
NLP	Natural Language Processing
PQP	Project Quality Plan
QA	Quality Assurance
QC	Quality Control
QMS	Quality Management Systems
SOR	Site Observation Reports
SPC	Statistical Process Control
TQC	Total Quality Control
TQM	Total Quality Management

Overview

Over the past decades, technological innovations have significantly transformed business practices across industries, with the construction sector experiencing particularly noteworthy benefits. Advancements such as Building Information Modeling, automated and robotic construction technologies, and advanced project management software have revolutionized the planning, execution, and management of construction projects (Regona et al., 2023). These tools have enhanced precision in planning, improved stakeholder communication, and optimized resource allocation, contributing to better management of project scope, cost, time, and quality. Despite these advancements, the construction industry continues to lag behind other sectors in fully leveraging emerging technologies like Artificial Intelligence (AI) to address persistent challenges in quality management (Dip Datta et al., 2024).

The construction industry continually faces difficulties in maintaining quality standards, particularly in large and complex infrastructure projects like the Jeddah Stormwater Program (JSWP). These projects involve numerous stakeholders, dynamic conditions, and high volumes of simultaneous activities, which strain traditional Construction Quality Management (CQM) practices. Issues such as material defects, utility conflicts, and inadequate compliance monitoring frequently lead to delays, cost overruns, and reduced stakeholders or customer satisfaction. Addressing these challenges requires innovative solutions, and this study explores the potential of AI enhanced CQM systems.

This research is significant for both theoretical and practical reasons. Theoretically, it investigates AI's role as a moderating variable, examining how it can optimize CQM practices and mitigate the negative impacts of project size and complexity on outcomes such as cost, time, quality, and customer satisfaction. Practically, the research will focus on some AI driven technology such as machine learning, predictive analytics, natural language processing, and real-time monitoring to improve predictive capabilities, decision-making, defect detection, and automation of quality control and assurance processes in infrastructure projects. By addressing challenges associated with AI adoption, such as costs, technical expertise, and organizational resistance, this study provides actionable insights into leveraging AI technologies in CQM.

The study is guided by three research questions: (1) the limitations of current CQM practices in large infrastructure projects, (2) the moderating role of AI in enhancing project outcomes, and (3) the barriers to adopting AI in construction projects. Through these questions, the research aims to contribute to the growing body of knowledge in construction quality management and provide a practical framework for AI adoption.

This study's findings are expected to offer substantial value by addressing the gaps in traditional CQM practices and demonstrating the transformative potential of AI in complex construction environments. Focusing on JSWP, the research not only highlights challenges unique to large-scale projects but also provides a replicable model for integrating AI into construction quality management globally.

Keywords

Quality Management, AI, Construction Project Outcomes, Case Study – Saudi Arabia, Stormwater, Machine Learning, Natural Language Processing.

Problem statement

The Saudi Vision 2030 outlines a bold roadmap for national transformation, with infrastructure development playing a pivotal role in improving the quality of life for citizens, fostering vibrant cities, and promoting environmental responsibility. The construction industry is instrumental in realizing these infrastructure goals that demand robust quality management in construction, highlighting the potential of AI to transform quality practices (Vision2030, n. d.). Despite its promising potential, AI adoption Saudi Arabian construction industry remains significantly behind the global trend of technological innovation. Effective quality management is crucial for complex construction projects, yet the impact of CQM can be influenced significantly by technological factors, particularly AI (Neyestani, 2016). Research is crucial to understanding AI's moderating role and its capacity to enhance CQM by exploring how AI-powered data analysis can preemptively identify quality issues, reduce work, predict project risks, and optimize resource allocation.

Challenges in Implementing Quality Management in Construction

Implementing quality management in construction, despite its well-recognized benefits, remains a significant challenge for many organizations. Several factors contribute to the difficulties in effectively implementing robust quality management systems in the construction industry. Firstly, Zakaria et al. (2017) and Leong et al. (2014) indicated that a major challenge in the construction industry is its project-based nature, where each project is unique and often involves numerous stakeholders, subcontractors, and varying site conditions. In contrast, industries such as manufacturing focus on the mass production of standardized products, allowing for greater control over processes and environments (Rezaei, 2011). This fundamental difference significantly influences how construction projects define, measure, and manage quality.

Secondly, the fragmented and decentralized nature of the construction industry makes it challenging to implement organization-wide quality management systems. The high degree of customization in construction projects, the dynamic nature of construction activities, and site-specific conditions inherent in construction projects make it difficult to standardize processes and achieve organization-wide quality control (Tang et al., 2005). Furthermore, construction projects often face constraints such as tight budgets, short timelines, and changing client requirements, which can compromise the ability to prioritize and invest in robust quality management practices.

Thirdly, the construction industry's resistance to change and a lack of awareness and commitment to quality management principles among some construction professionals can impede the successful adoption of quality management systems. These inherent complexities, along with deep-rooted cultural barriers within the industry, pose significant hurdles in realizing the full potential of quality management practices in construction projects. The reluctance to embrace new approaches and the entrenched mindsets of some construction stakeholders can create obstacles to implementing effective quality management initiatives, hindering the optimization of construction project outcomes (Abioye et al., 2021).

In addition to these factors, the author's experience with the JSWP has highlighted the inherent complexity and variability of construction projects, further complicating the implementation of robust quality management systems. JSWP, with its numerous ongoing and

unique projects spread across all sides of Jeddah, demonstrates how the involvement of multiple stakeholders, subcontractors, and ever-changing site conditions can challenge standardization and consistent quality control. These challenges are further compounded by varying levels of client involvement and the geographically dispersed nature of the projects and inadequate staffing levels, which strain supervision capacity and make it even more difficult to ensure adherence to quality standards.

Despite JSWP projects being similar in concept and executed by the same contractors, they continue to encounter persistent issues. These issues include material defects, supply and handling challenges, and inadequate quality control measures, which compromise the effectiveness and efficiency of the construction efforts. The projects need adequate supervision, which is exacerbated by the increased high volume of simultaneous projects, leading to frequent utility conflicts and substantial delays. These conflicts often result in prolonged processes for coordination with other stakeholders, modification and approvals of shop drawings and execution methods. Such delays increase resident complaints due to prolonged excavation works, extended closures of roads, escalating the cost of reworks, and extending the overall project's progress.

Additionally, constraints such as tight budgets, short timelines, customer satisfaction, and shifting client demand place pressure on prioritizing quality over immediate deliverables. Combined with that resistance to change and varying levels of awareness and commitment among construction professionals further impede the adoption of effective CQM. Addressing these challenges within JSWP, and more broadly in construction, requires a dedicated effort to foster a quality culture, enhance awareness, and leverage innovative solutions, such as AI-driven CQM practices, to streamline processes and deliver better project outcomes.

Recent study by Zakaria et al. (2017) identifies several challenges in flood mitigation projects that hinder successful implementation of CQM. These include inadequate planning, poor stakeholder coordination, ineffective resource allocation, and inconsistent adherence to project standards and master plans. Such challenges disrupt project workflows, lead to delays, and compromise overall project quality. Another study by Hwang and Yang (2014) highlights rework as a major contributor to project delays, with its root causes often tied to quality-related issues such as design errors, inadequate quality control, and poor adherence to project specifications. The research underscores the importance of proactive quality management in

minimizing rework, noting that early identification and resolution of potential quality issues can significantly reduce disruptions and improve project schedules.

Similar challenges are evident in JSWP, where gaps in planning, stakeholder alignment, and non-compliance with quality management processes, such as Method of Statements (MOS) and Inspection Testing Plans (ITP), exacerbate inefficiencies across its large-scale projects. The Taunsa Barrage Rehabilitation and Modernization Project in Pakistan study by Khan et. al (2006) highlights parallel issues, such as inadequate adherence to quality practices due to increased work load and complexity of work, underutilization of statistical sampling methods, and limited stakeholder awareness and commitment to quality practices, which significantly hinder Quality Assurance (QA) and Quality Control (QC) efforts.

These shared challenges underscore the need for robust, project-specific quality management practices to address recurring inefficiencies and ensure better outcomes. For JSWP, integrating AI-driven technologies could serve as a transformative solution, enabling automated compliance monitoring, optimizing resource allocation, and providing real-time insights. By addressing these foundational gaps and leveraging advanced technologies, JSWP can enhance coordination, reduce rework, and improve overall project performance across its dispersed and complex infrastructure initiatives.

However, more research will be needed to understand how integrating AI with quality management practices impacts construction project outcomes, particularly within the Saudi Arabian context (Datta et al., 2024). Existing global studies often emphasize the general advantages of AI in construction, such as its impact on project outcomes or its application to specific quality management issues. However, they rarely address the unique challenges and established practices specific to the Saudi Arabian construction sector nor quality management system. Therefore, more focused research is needed to investigate and understand the effect of AI on the overall CQM, to ensure our understanding of effectively integrating these technologies with existing quality practices to optimize project outcomes.

Purpose of the Study

Given the potential benefits of AI in improving construction project outcomes through enhanced quality management, this research aims to explore the moderating role of artificial

intelligence in improving the effectiveness of CQM practices in construction projects. The study will focus on infrastructure projects, which are typically complex and involve multiple stakeholders. They are crucial in driving economic growth, improving quality of life, and fostering long-term sustainability in the Saudi Arabian construction industry. The specific objectives of the study are:

1. **Comprehensive Review:** Conduct a comprehensive review of empirical studies that investigate the impact of AI on construction CQM practices and project outcomes, aiming to synthesize key findings and identify gaps in the current literature.
2. **Evaluate CQM Practices:** Assess the limitations of traditional CQM practices in addressing the challenges posed by the size and complexity of infrastructure projects, particularly within JSWP.
3. **Examine AI's Impact:** Investigate the potential of AI technologies to enhance CQM practices focusing on AI's moderating role in mitigating CQM practices insufficiencies, with a focus on improving project outcomes such as cost efficiency, schedule adherence, quality, and customer satisfaction.
4. **Identify AI challenges:** Based on insights gathered from the selected contractors and projects data, identify and analyze the challenges associated with implementing AI-driven CQM practices in infrastructure projects.
5. **Develop Strategies and Frameworks:** Propose practical strategies and frameworks for effectively integrating AI-driven CQM practices, ensuring improved outcomes in large and complex infrastructure projects.
6. **Explore future opportunities:** Explore emerging opportunities for AI to enhance CQM practices in infrastructure projects further and outline future research directions based on the findings from the study.

Significance of Study

Theoretical Contributions: This research seeks to fill a significant gap in construction management literature by empirically investigating the moderating role of AI in quality management within construction projects. It will enhance theoretical frameworks by integrating advanced AI technologies, such as Machine Learning (ML) and Natural Language Processing (NLP) and examining their impact on the effectiveness of quality management practices. This study will contribute to a deeper academic understanding of how AI can be systematically applied to improve construction project outcomes, through enhanced CQM

practices offering a new perspective on the interplay between technology and project management.

Practical Implications: The study is poised to offer substantial value to the construction industry, particularly within the context of JSWP. The findings will help develop more efficient, cost-effective, and high-quality construction practices by exploring and validating AI-driven quality management approaches. The insights gained could lead to the development of refined AI-enhanced quality management frameworks that reduce rework, delays, cost, and improve stakeholder satisfaction, thus providing a model for future construction projects in Saudi Arabia.

Expected Added Value: The integration of AI in managing complex infrastructure projects, as explored in this study, aligns with the strategic goals of Saudi Vision 2030. The successful application of AI in the JSWP could serve as a benchmark for the national construction industry, promoting broader adoption of intelligent technologies. This research will provide actionable strategies for leveraging AI to overcome common quality management challenges, enhancing project delivery across the board. Furthermore, the study recommends that policymakers, project managers, and industry professionals adopt AI-driven solutions, potentially transforming construction practices nationally and internationally.

Research Methodology

This study employs a mixed-methods research approach, combining in-depth qualitative case studies and comprehensive quantitative data analysis, to thoroughly investigate the relationship between CQM practices, construction project outcomes, and the moderating influence of Artificial Intelligence technologies. The qualitative component will provide rich contextual insights, exploring how AI-enabled CQM processes are implemented and integrated within real-world construction projects. The quantitative analysis will then examine the statistical significance and magnitude of the moderating effect of AI on the link between CQM and key project outcomes, such as reduced rework, enhanced productivity, and improved cost and schedule performance. This holistic mixed-methods approach will yield a deeper understanding of the complex interplay between quality management, AI, and construction project success.

Data Collection, Sampling and Analysis

Primary data will be collected through structured surveys from stakeholders involved in JSWP, including project managers, quality professionals, construction teams, contractors, suppliers, and AI technology experts. Secondary data will be gathered from project documentation, industry reports, academic journals, case studies, and other relevant literature on the application of Artificial Intelligence technologies in the context of construction quality management. This comprehensive secondary data collection will provide a robust understanding of the current state of research and industry practices in leveraging AI to enhance not only project management, but also quality management processes and outcomes in construction projects.

Purposive sampling will be employed to ensure participants have direct experience with CQM practices or AI implementation, with an estimated sample size of approximately 50-70 participants from JSWP stakeholders (Client, Consultants, Contractors, Sub-Contractors, and Suppliers). To ensure comprehensive insights, the sample will include a diverse set from various roles within the JSWP projects. **Project Managers** can provide perspectives on overall project execution and quality management integration, while **Quality Control and Assurance Teams** can highlight the application and challenges of current CQM practices. **Engineers and Site Supervisors** offer practical insights into quality-related issues and AI implementation on-site. Additionally, involving other key disciplines such as **Planning Engineers** allows for exploring how AI can optimize scheduling, anticipate delays, and enhance time management. **Cost Control Engineers** can contribute insights into cost forecasting and budget management, focusing on how AI aids in controlling project expenses. **Technical Engineers** provide knowledge about design and specifications, and utility issues, emphasizing AI's role in streamlining technical solutions and design reviews. **Clients or Regulatory Representatives** ensure a focus on compliance and stakeholder satisfaction, while **AI or Technology Specialists** can offer expertise on the deployment and potential of AI technologies. This multidisciplinary approach ensures a holistic understanding of the integration of AI into CQM practices in large infrastructure projects. Quantitative data from surveys will be analyzed using statistical Tools such as SPSS.

Theoretical background

The concept of quality management has evolved significantly since its early applications in manufacturing, transforming industries by promoting consistency, efficiency, and customer satisfaction. Initially focused on basic inspection and defect detection, quality management has developed into a sophisticated system that integrates planning, control, and continuous improvement to enhance organizational performance. This evolution reflects an increasing awareness that quality is not merely a production issue but a fundamental organizational objective (Daneshjo et al., 2021). In construction, where project complexity and stakeholder expectations are high, robust quality management is crucial for meeting performance goals and sustaining competitive advantage.

Several pioneering figures, often called quality management "gurus," laid the groundwork for modern quality practices. **Walter Shewhart**, often called the father of statistical quality control, introduced the concept of **control charts** to monitor process variability in the 1920s. Building on Shewhart's ideas, **W. Edwards Deming** promoted continuous improvement through his **PDCA cycle** (Plan-Do-Check-Act) and emphasized data-driven decision-making. In the 1950s, **Joseph Juran** introduced the **Quality Trilogy**—quality planning, control, and improvement—which underscored the importance of quality as a company-wide responsibility (ASQ, 2024). **Philip Crosby** added to this foundation with his philosophy of **zero defects** and the idea that "quality is free," advocating for preventive measures over costly corrections. **Armand Feigenbaum** introduced **Total Quality Control (TQC)**, asserting that quality should be integrated across all departments (Huggins, 1998). At the same time, **Kaoru Ishikawa** emphasized the role of collaborative problem-solving and developed tools like the **fishbone diagram** for root-cause analysis.

These contributions have influenced modern project management, where achieving project success depends on balancing the **Triple Constraint**, scope, cost and time. In construction, changes to any of these factors, such as an accelerated timeline, can impact both the budget and the quality of the outcome, posing significant challenges for project managers. **Customer satisfaction** further reinforces these constraints to measure project success, reflecting whether the project meets or exceeds client expectations. The principles established by the quality pioneers provide a theoretical foundation for understanding how quality management

practices can help optimize this balance, especially when complemented by modern tools such as AI driven technology.

Construction Quality Management (Independent Variable)

This study examines the impact of quality management practices in construction on project outcomes, with AI technology as a moderating factor. It is important to understand the key elements of Construction Quality Management and how it is applied in industry. CQM is vital to the construction industry as it directly influences project outcomes, minimizes costs associated with rework, and improves efficiency. Effective CQM practices ensure that project phases is executed according to client expectations and regulatory standards (Luo et al., 2022).

The PMBOK (PMI, 2021, p.xx) defines Quality Management as "the process of determining quality policies, objectives, and responsibilities so that the project will satisfy the needs for which it was undertaken." CQM involves applying these principles to ensure project deliverables meet all required standards, specifications, and client expectations, focusing on consistent quality throughout construction.

Philip Crosby advocates for defining quality as "conformance to requirements," focusing on objectively meeting predetermined specifications and standards. This concept is fundamental in the planning phase of construction projects, where a clear, measurable framework for quality management supports Crosby's zero-defects philosophy, emphasizing the prevention of defects from the outset. Planning for quality early in the project ensures that project specifications fulfill client requirements and regulatory standards (ASQ, 2024).

Expanding on Crosby's view, Juran and Godfrey (1999) introduces "fitness for use" as a core aspect of quality, highlighting the importance of ensuring that the constructed facility effectively serves its intended purpose and meets the end-user's needs. This approach extends beyond compliance with specifications to emphasize functionality, reliability, and durability, considering the structure's performance over its entire lifecycle.

Furthering this perspective, Khan et al. (2008) suggest that quality in construction encompasses the fulfillment of stakeholder expectations. Quality management must address the needs of not only the client but also contractors, subcontractors, designers, and the

community, ensuring that the final project meets broad expectations. This holistic approach aligns with CQM, which Sogaxa et al. (2021) defines as "a management approach that aims to ensure that the construction process is completed within the specified quality requirements, on time, within budget, and safely." Similarly, Neyestani (2016) describes CQM as "the coordination and integration of all quality assurance and quality control activities throughout the life of the project to achieve the project objectives." These perspectives emphasize that effective CQM requires aligning quality planning, control, and assurance efforts to fulfill all project objectives, from specifications to stakeholder satisfaction.

The author defines CQM as a systematic process supported by strategic goals established earlier during the project planning stage toward fulfilling project quality objectives through a preventive approach. This approach can be enhanced by using AI as a predictive tool to improve efficiency, prevent defects, and reduce the cost of reworks in construction projects by preventing defects before they occur.

Construction Quality Management is essential to deliver projects efficiently, meeting quality standards, and satisfying client expectations. **ISO 9001** offers a standardized approach to quality management, emphasizing clear documentation, consistent processes, and compliance with international standards. It is particularly beneficial for ensuring that construction projects meet regulatory requirements and maintain consistent quality. **Total Quality Management (TQM)** promotes a quality-centered culture across all levels of an organization, which fosters accountability and teamwork, which are essential for complex construction projects (Pheng & Teo, 2003). **Lean Construction** focuses on minimizing waste and maximizing value, directly supporting efficient resource management, a critical aspect of quality planning and control in construction. **Six Sigma** provides a structured, data-driven approach to reduce defects and improve process consistency, enhancing Quality Control and Quality Improvement through measurable results (Ferng & Price, 2005).

Among these, however, Juran's Quality Trilogy—emphasizing Quality Planning, Quality Assurance & Control, and Quality Improvement—provides a balanced, comprehensive framework particularly well-suited to the needs of construction projects. Unlike broader organizational approaches, Juran's Trilogy is adaptable to unique construction challenges, allowing for proactive planning, real-time control, and continuous improvement throughout the project lifecycle (Juran & Joseph, 2012). These three interconnected dimensions address

the preventive and corrective needs in construction quality management, making Juran's Trilogy an ideal foundation for effective CQM in achieving high-quality, efficient, and timely project outcomes.

Quality Planning

The PMBOK (PMI, 2021) defines **Quality Planning** as "the process of identifying quality requirements and/or standards for the project and its deliverables and documenting how the project will demonstrate compliance." It aligns with Juran's definition of establishing the goals and process required to meet quality standards from the outset (Juran and Godfrey, 1999). In the construction industry, this means defining the necessary quality standards for materials, processes, and final outputs, setting clear expectations for quality from the outset, and establishing procedures for meeting these standards. Effective quality planning is crucial for establishing quality benchmarks, defining roles and responsibilities, and documenting the quality management strategy. A well-crafted quality plan will delineate the actions undertaken at each project phase to attain the targeted quality standards (Neyestani, 2016).

Quality Assurance & Control

In Construction Quality Management, **Quality Assurance (QA)** and **Quality Control (QC)** play complementary roles in maintaining and improving project quality. According to the PMBOK (PMI, 2021), QA is "the process of auditing the quality requirements and the results from quality control measurements to ensure appropriate quality standards and operational definitions are used." QA in construction is proactive, aiming to prevent defects through regular inspections, testing, and monitoring, ensuring that work meets the established quality plan and specifications. Juran's Quality Control Handbook (Juran & Godfrey, 1999) expands on this by defining QA as a process that instills confidence that quality requirements will be met throughout the project. Juran emphasizes the importance of developing robust systems and preventive measures and conducting audits to verify compliance with quality standards and ensure consistency and reliability across project phases

Quality Control on the other hand, is more hands-on and focuses on detecting and correcting quality issues. Defined by Juran & Godfrey (1999) as "the process of evaluating quality performance, comparing that performance with standards or goals, and acting on the difference," QC emphasizes feedback loops and corrective actions, making it a cyclical

process aimed at continuous improvement. QC includes practical, operational techniques for measuring and controlling the characteristics of materials, structures, and systems to meet quality requirements. It operates as a "detection mode," identifying existing issues and facilitating corrective actions. QC systems provide displays of non-conformance to highlight areas requiring attention, allowing for data-driven problem identification and management (Tang. et. al, 2005). In construction, QC procedures often include daily inspections, quality reporting, and minimizing output variation, ensuring that standards are consistently met across all project stages.

In the construction industry, QA and QC form a comprehensive quality framework in CQM. QA establishes preventive processes and systems, while QC detects and addresses deviations from quality standards. This dual approach is essential in construction, where complex projects demand proactive quality assurance and rigorous control over the work that will be executed.

Quality Improvement

The third component of Juran's Quality Trilogy, Quality Improvement, is defined by PMBOK (PMI, 2021) as "the process of enhancing the organization's processes to improve the project's outcomes" This dimension continuously refines processes, systems, and practices to improve construction quality, reliability, and consistency. Quality Improvement involves analyzing performance, identifying opportunities for enhancement, and implementing changes to address the root causes of issues. Common practices include post-project reviews, benchmarking against industry standards (Crosby, n.d), and incorporating Lean Construction and Six Sigma methodologies to streamline processes and minimize inefficiencies. By embracing a culture of continuous improvement, construction organizations can systematically enhance the quality of their project deliverables and outcomes over time.

Construction Projects outcomes (dependent Variable)

Construction project outcomes are multidimensional, encompassing factors such as safety, schedule, cost, and customer satisfaction. Effective quality management is crucial to achieving positive project outcomes across these critical dimensions. PMBOK defines project outcomes as the **outputs and benefits** that result from project activities, which should align with the organization's strategic objectives and provide value to stakeholders. ISO 21500 defines

project outcomes as meeting the predefined criteria for success, including cost, time, quality, and stakeholder satisfaction.

This study measures project outcomes by four key indicators: Cost, Time (or Schedule), Quality, and Customer Satisfaction. These indicators are chosen in this research as they are universally recognized and used as the core dimensions of project performance in construction management. Cost represents the financial efficiency of the project, aiming to minimize expenses while maintaining standards. Time (or Schedule) measures adherence to timelines, as delays can lead to cost overruns and client dissatisfaction. Quality ensures the project meets all specifications and is durable, safe, and fit for purpose. Also, Poor quality can lead to rework, increased costs, safety hazards, failure to meet regulatory requirements, and reduced customer satisfaction (Hwang & Yang, 2014). Prioritizing quality ensures that the final product fulfills its intended purpose and provides long-term value to the client and end-users. Finally, customer Satisfaction reflects the degree to which the project meets or exceeds client expectations, which is crucial in assessing the project's overall success. These four indicators are interdependent and collectively capture the balance of efficiency, effectiveness, and stakeholder value that defines a successful construction project (Neyestani, 2016) (Kiew et al., n.d.).

Project outcomes are particularly crucial in construction, as they determine the project's viability, efficiency, and overall quality, directly impacting client and end-user satisfaction. Effective project outcomes are essential in the construction industry, where complex, large-scale projects require adherence to high standards and regulatory compliance (Low & Ong, 2014). Construction projects are complex, involving multiple stakeholders, regulatory requirements, and high-risk activities. Managing cost, time, quality, and customer satisfaction is essential to navigate these complexities. By integrating AI technology into quality management, the study aims to enhance these outcomes, demonstrating practical relevance.

Artificial Technology (Moderating Variable)

Several sources defined Artificial Intelligence (AI) and its related technologies, emphasizing its role in developing intelligent machines that can perform tasks traditionally requiring human intelligence (Chouchene et al., 2020). AI is a branch of computer science dedicated to creating machines capable of visual perception, speech recognition, decision-making, and

language translation. Some definitions focus on AI's ability to mimic or replicate human cognitive functions, such as thinking, creativity, and planning (Nagireddy, 2023). Additionally, AI combines computer science and large datasets to solve complex problems, automating tasks typically reliant on human intelligence. In broader terms, AI is the science of developing intelligent systems and models that can replicate human cognitive processes, thus creating systems that enhance and streamline various tasks across multiple industries (Abioye et al., 2021).

AI technology includes tools like ML, CV, NLP, and predictive analytics, which significantly benefit many fields, including construction. ML helps identify patterns in large datasets, enabling predictive insights, while CV automates inspections and defect detection, improving accuracy. These technologies streamline tasks, reduce errors, and enhance decision-making, offering efficient, data-driven support to complex projects (Sahadevan, 2023).

Several AI platforms offer robust tools suited explicitly for data analysis that can support quality management in construction by predictive modeling and process automation. **Google AutoML** enables users to create custom ML models that detect patterns and predict outcomes without extensive coding expertise (Google Cloud, 2024). **Microsoft Azure AI** provides a suite of AI services, including CV and NLP, that can automate inspections, detect defects, and facilitate project monitoring in real-time (Microsoft, 2024). **IBM Watson** offers advanced predictive analytics and ML capabilities to process complex construction data to forecast potential risks and support data-driven decision-making (IBM, 2024).

In construction, AI technology transforms quality management practices by providing real-time insights, automating quality inspections, and predicting potential issues before they arise. For instance, computer vision algorithms can detect defects during construction activities, reducing reliance on manual inspections and improving accuracy. Predictive analytics, powered by platforms like IBM Watson, help identify trends in project data that could indicate future problems, allowing proactive measures to be implemented. These AI capabilities align well with Deming, Juran, and Feigenbaum's quality management theories, reinforcing data-driven decision-making, strategic planning, and organization-wide quality efforts. By integrating AI as a moderating variable, construction projects can achieve more efficient, consistent, and reliable quality outcomes, meeting evolving demands in the industry (Seyman-Güray, 2023).

Conclusion

Integrating quality management theories with AI technology provides a comprehensive framework for understanding and improving construction project outcomes. By grounding this research in the philosophies of quality management pioneers, this study aims to demonstrate how AI can systematically enhance the effectiveness of quality management practices, ultimately leading to better outcomes in cost, time, quality, and customer satisfaction within the construction industry.

Practical Background

The Jeddah Storm Water Program, tasked with a significant overhaul of the city's stormwater management systems, involves 89 projects that incorporate similar construction activities such as excavation, laying network pipes, installation of manholes and catch basins, and construction of marine outfalls and pumping stations. The JSWP was chosen as a case study as these projects face significant challenges in maintaining quality standards due to the complexity of the work, tight timelines, and the dynamic nature of the construction environment as well as utility clashes. This setting offers a unique opportunity to investigate how CQM practices perform under demanding conditions and to evaluate AI's potential to address these challenges effectively (JSWP, 2021).

Despite the projects being similar in concept and executed by the same contractors, these projects consistently face recurring challenges that hinder their progress. Issues such as material defects, supply and handling difficulties of materials, lack of site supervision, and inadequate quality control measures compromise construction efficiency and effectiveness. Additionally, the high volume of simultaneous projects strains supervision capacity, leading to frequent utility conflicts and significant delays. These conflicts often result in prolonged design changes and approvals, frequent shop drawing modifications, extended excavation activities, escalating rework costs and increasing resident complaints. Together, these factors disrupt the JSWP program timelines and negatively impact overall project outcomes.

Moreover, a critical challenge exacerbating these problems is some contractors' non-compliance with established work procedures and method statements. This disregard for producers leads to quality issues and undermines strategic quality management efforts to meet project standards. Integrating advanced monitoring and compliance technologies, such as AI,

is imperative. Projects can promptly identify deviations and enforce corrective actions by leveraging AI to automate compliance checks and monitor adherence to method statements in real-time. This proactive approach mitigates the risk of non-compliance and enhances overall project delivery.

Compounding these challenges, the risk associated with the rainfall season can have severe impacts on both ongoing construction projects and surrounding residential areas if not managed promptly and effectively. The dynamic nature of construction, coupled with tight timelines, heightens the risk of disruptions. Effective quality management, supported by AI-driven predictive analytics and automation, can mitigate these risks, ensuring projects are delivered efficiently, on budget, and to high standards.

Integrating AI technologies into JSWP offers transformative solutions to overcome the recurring challenges faced by the program's projects. AI-driven tools, such as predictive analytics and real-time monitoring systems, can enhance material quality control by identifying defects and optimizing supply chain management. Automated compliance systems ensure strict adherence to method statements and established protocols, reducing the risk of quality lapses caused by contractor non-compliance. Furthermore, AI's ability to forecast potential conflicts, such as utility clashes, and simulate design scenarios enables proactive planning, minimizing delays and costly rework. During critical periods like the rainfall season, AI's predictive capabilities can help anticipate risks, prioritize interventions, and safeguard ongoing projects and surrounding residential areas. By leveraging AI, JSWP can significantly enhance the efficiency, consistency, and effectiveness of Construction Quality Management practices, ensuring improved project outcomes despite the complexities and dynamic conditions of the program.

This research aims to fill the gap by focusing on integrating AI into CQM practices, particularly in stormwater network projects, examining several vital aspects, and identifying the most impactful ways to tailor AI solutions to the unique context of Saudi Arabia's construction industry. Successful Integration of AI will benefit JSWP in overcoming some of the quality issues and concerns in the following four significant areas of quality management:

1. **Quality Planning:** Exploring how AI-enhanced planning can improve overall quality and mitigate cost overruns and delays, improving economic and temporal efficiency in stormwater network projects.

2. **Quality Control:** Analyzing how AI-driven tools detect/predict and correct defects early in construction.
3. **Quality Assurance:** Assessing AI's role in enhancing adherence to quality standards and related project requirements, which are crucial for the integrity of stormwater projects.
4. **Quality Improvement:** Investigating how AI contributes to the sustainability and resilience of stormwater networks, mainly through failure detection, and recommending preventive measures based on pattern recognition from historical data.

Against this backdrop of exploring AI's potential to transform areas of CQM practices, the research is structured around three critical questions:

Research Question 1: Does CQM practices become insufficient in addressing the challenges of size and complexity in infrastructure projects, and how does this inadequacy negatively impact project management outcomes?

- **Question 1.1:** Do the challenges of managing large and complex infrastructure projects lead to schedule delays, as CQM practices become inadequate in mitigating challenges?
- **Question 1.2:** Do the size and complexity of infrastructure projects contribute to cost overruns, as CQM practices become insufficient in preventing these overruns?
- **Question 1.3:** Do the size and complexity of infrastructure projects negatively affect customer satisfaction, and CQM practices are unable to address these concerns effectively?
- **Question 1.4:** Do the size and complexity of infrastructure projects result in substandard quality outcomes, as CQM practices fail to maintain consistent quality under such conditions?

Research Question 2: Do the AI-driven CQM practices in JSWP modify the impact relationship between quality management and project management outcomes?

- **Question 2.1:** Do the AI-driven practices of Quality Planning in JSWP modify the impact relationship between quality management and project management outcomes?
- **Question 2.2:** Do the AI-driven practices of Quality Control in JSWP modify the impact relationship between quality management and project management outcomes?
- **Question 2.3:** Do the AI-driven practices of Quality Assurance in JSWP modify the impact relationship between quality management and project management outcomes?
- **Question 2.4:** Do the AI-driven practices of Quality Improvement in JSWP modify the impact relationship between quality management and project management outcomes?

Research Question 3: What are the financial, organizational, ethical and technical challenges associated with adopting AI technologies in construction projects, and how do these barriers impact the effective integration of AI into CQM practices?

- **Question 3.1:** Does the cost of implementing AI technologies create significant barriers to their adoption in CQM practices?
- **Question 3.2:** Does resistance to change among stakeholders and organizational culture negatively impact the adoption of AI technologies in construction projects?
- **Question 3.3:** Does the lack of high-quality data, integration challenges, or insufficient technical expertise hinder the effective implementation of AI in CQM?
- **Question 3.4:** Does the skills gap in the construction industry limit the adoption and successful utilization of AI technologies?
- **Question 3.5:** Do concerns about data privacy, algorithmic bias, and regulatory compliance affect the willingness of construction organizations to adopt AI technologies?

Hypothesis

CQM is essential for ensuring projects' success and sustainability in the rapidly evolving construction industry. With the ongoing development of AI, there is significant interest in leveraging its capabilities to enhance the efficiency, accuracy, and overall outcomes of CQM practices. Through this approach, the study aims to offer a comprehensive analysis of AI's role in refining CQM processes and its broader implications on the efficiency and success of infrastructure projects, particularly in stormwater network management. The following hypotheses were formulated to guide this investigation:

Hypothesis (H1):

CQM practices become insufficient in addressing the challenges posed by the size and complexity of infrastructure projects, leading to negative impacts on project management outcomes, including cost, schedule adherence, quality, and customer satisfaction.

- **Hypothesis (H1a):** CQM practices become insufficient in maintaining work quality as size and complexity of infrastructure projects increase, negatively impacting deliverable quality.
- **Hypothesis (H1b):** CQM practices fail to prevent cost overruns in large and complex infrastructure projects, resulting in increased project costs.

- **Hypothesis (H1c):** CQM practices are less effective in ensuring adherence to project schedules in large and complex infrastructure projects, leading to significant delays.
- **Hypothesis (H1d):** The insufficiency of CQM practices in addressing the challenges of size and complexity negatively impacts customer satisfaction in infrastructure projects.

Hypothesis (H2):

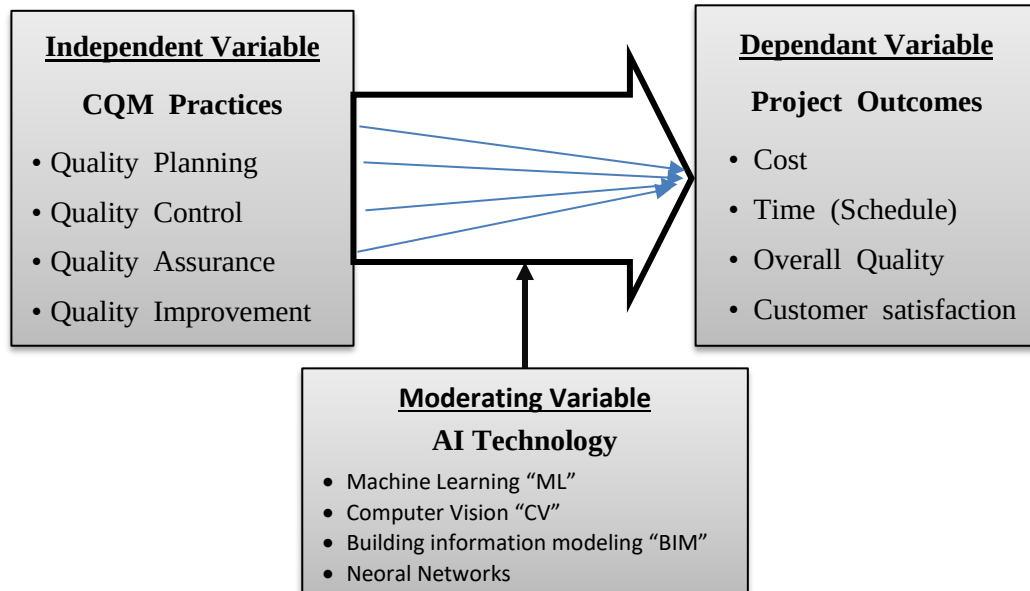
AI-driven CQM practices in JSWP significantly modify the relationship between CQM practices and project management outcomes, enhancing cost efficiency, schedule adherence, quality of deliverables, and customer satisfaction.

- **Hypothesis (H2a):** AI-driven CQM practices significantly enhance the quality of deliverables in infrastructure projects by improving defect detection and reducing rework.
- **Hypothesis (H2b):** AI-driven CQM practices significantly reduce cost overruns in infrastructure projects by reducing the cost of rework and cost of poor quality.
- **Hypothesis (H2C):** AI-driven CQM practices significantly reduce schedule delays in infrastructure projects by minimizing rework through proactive defect detection and quality monitoring.

Hypothesis (H3): Financial, organizational, ethical, and technical challenges significantly hinder the effective integration of AI technologies into CQM practices in infrastructure projects.

- **Hypothesis (H3a):** Financial constraints, such as high implementation and operational costs, significantly limit the adoption of AI technologies in CQM practices.
- **Hypothesis (H3b):** Organizational barriers, including resistance to change and a lack of skilled personnel, significantly impact the successful integration of AI into CQM practices.
- **Hypothesis (H3c):** Ethical concerns, such as data privacy, algorithmic bias, and job displacement fears, significantly hinder the adoption of AI technologies in CQM practices.
- **Hypothesis (H3d):** Technical challenges, including insufficient data quality and integration difficulties, significantly reduce the effectiveness of AI technologies in improving CQM practices.

The following diagram illustrates the conceptual framework for this study, highlighting the relationships between the independent variable (**Construction Quality Management Practices**), the dependent variable (**Project Management Outcomes**), and the moderating role of (**AI Technologies**).



The diagram represents the variables and their relationships

Source: prepared by the researcher

Literature Review

Quality Management Systems in Construction

Quality management systems are crucial for improving the performance of organizations, especially in the construction industry. Research has shown that QMSs can significantly impact customer satisfaction, cost control, time management, and overall quality (Leong et al., 2014) (Aichouni et al., 2014). Neyestani (2016) emphasizes the impact of QMS on these four crucial aspects of construction projects. Furthermore, a study in the Saudi construction industry supports Oakland & Marosszeky's (2006) statement that the industry needs to embrace total quality management concepts and QMS, especially during growth and rapid expansion.

The effectiveness of a quality management system in construction projects can provide better control over project processes and workflows. Studies conducted across diverse construction markets, including Saudi Arabia, UAE, India, China, Pakistan, USA, and South Africa, have all demonstrated the benefits of implementing robust quality management systems to enhance project outcomes, improve cost control, enhance time management, and increase overall customer satisfaction and industry performance (Likita et al., 2018).

Challenges in Implementing CQM

The study conducted by Hamdan (2024) on a stormwater network project in the UAE highlighted that the strict implementation of CQM practices is critical for meeting required standards and customer needs. Such an adherence not only increases the project's lifecycle but also reduces maintenance costs and improves sustainability. The author explained on the case study the importance of implementing quality processes and procedures at every stage of the project, including material testing, site activities, and project documentation, such as shop drawings, MOS and ITP. In the context of JSWP, shop drawings, MOS and ITP have proven to be a significant challenge, as contractors often fail to adhere to these requirements as outlined in the quality plan. This non-compliance undermines the effectiveness of CQM practices, leading to recurring issues such as substandard workmanship, defects, and rework.

Another study by Othman et. al. (2018) highlights other challenges in implementing Quality Management Systems (QMS) in Malaysian construction projects for high rise construction, including limited knowledge of QA/QC procedures, inadequate supervision, and poor worker attitudes. These challenges are compounded by high material waste and excessive workloads for QA/QC personnel, leading to inefficiencies in achieving quality standards. The study proposes a structured framework to address these issues, emphasizing management commitment, enhanced documentation, and resource optimization.

A study conducted in Jordan by Khatatbeh, A. (2014) underscores significant challenges that impede effective QM practices, including a lack of senior management commitment, insufficient planning for quality management, poor coordination between stakeholders, and unclear allocation of quality responsibilities. Additionally, the findings reveal that inadequate staff training and resistance to adopting structured quality frameworks hinder the consistent application of QM processes. These challenges collectively impact the ability of construction projects to meet desired quality standards, emphasizing the need for stronger organizational alignment and proactive quality planning to overcome these obstacles.

The case study by Abdullah et al. (2008) examines the implementation of QMS in the Kuala Lumpur International Airport (KLIA) project, emphasizing the challenges associated with managing quality in large-scale and complex projects. The study highlights issues such as integrating multiple Project Quality Plans (PQP), coordinating diverse stakeholders, and ensuring compliance with statutory requirements and project-specific standards. These challenges were addressed through structured processes for inspections, testing, and audits.

Similarly, The Jeddah Stormwater Program exemplifies the critical importance of CQM in addressing the common challenges faced worldwide in large-scale, complex construction projects. As a multifaceted endeavor, JSWP demands meticulous planning, rigorous quality control, and a commitment to continuous improvement to mitigate the impact of size and complexity on project outcomes. Insights from case studies highlight the difficulties of integrating multiple PQP, coordinating diverse

stakeholders, and ensuring compliance with statutory and project-specific standards challenges mirrored in the JSWP. The UAE stormwater network case emphasizes the importance of strict adherence to quality management processes, including MOS and ITP, to prevent non-compliance, defects, and rework.

By leveraging the principles of Juran's Quality Trilogy, including quality planning, assurance, and improvement, and incorporating AI-driven solutions, the JSWP can address these challenges proactively. AI technologies, such as automated compliance monitoring and predictive analytics, can enhance planning accuracy, streamline quality control measures, and identify improvement opportunities across the program's dispersed projects. Together, these approaches can enable the delivery of a high-quality, efficient, and timely stormwater management system for the city of Jeddah, ensuring alignment with both project goals and stakeholder expectations.

Quality Planning

Quality planning is crucial to effective QMS in construction projects. It involves clearly defining the project requirements, identifying the critical quality characteristics that must be addressed, and establishing specific quality goals and objectives to be achieved. This comprehensive planning process helps ensure that the overall project scope, detailed drawings, and technical specifications are well-defined and unambiguous. This clarity is a prerequisite for maintaining high-quality construction processes and workflows throughout the project lifecycle. (Akinradewo et al., 2019).

In complex infrastructure projects where multiple stakeholders and intricate interdependencies are involved, comprehensive quality planning is vital for coordinating processes and ensuring collaboration. Effective planning establishes clear goals, defines critical quality characteristics, and maps workflows and control measures. However, in the JSWP, quality planning has often been insufficiently executed, as evidenced by numerous cases of work commencement without obtaining mandatory approvals. This lack of adherence to project quality procedures highlights a significant gap in ensuring consistency and alignment in the project's quality management efforts.

Quality Assurance

Quality assurance is a critical component of effective QMS in the construction industry. It involves implementing a comprehensive set of planned and systematic activities to ensure the constructed facility or infrastructure meets the specified requirements and customer expectations (Juran & Joseph, 2012). Quality assurance encompasses various activities, including inspection, testing, auditing, and monitoring, verifying that the construction processes and materials conform to established standards and specifications. However, in the JSWP, gaps in quality assurance practices have been observed, such as inconsistent inspection routines and inadequate adherence to ITP, often due to the high volume of concurrent projects and strained supervisory capacity. These shortcomings have led to instances where quality issues were only identified after significant work was completed, resulting in rework and delays. By addressing such gaps and implementing robust quality assurance measures, construction projects can enhance the overall quality, reliability, and longevity of the constructed facilities, ultimately meeting or exceeding client requirements and expectations.

Quality Improvement

As per Juran & Joseph (2012) quality improvement targets two main areas: enhancing product features and reducing deficiencies. Improving product features increases customer satisfaction by introducing innovative designs, sustainable materials, or advanced construction techniques. Reducing deficiencies minimizes waste, rework, and delays, thus boosting efficiency.

In JSWP, the lack of a structured approach to continuous quality improvement has often led to repeated deficiencies, such as material waste and recurring design modifications, due to inadequate coordination, especially with other utilities' providers, and poor communication among stakeholders. These recurring issues highlight the importance of adopting principles like a customer focus to meet stakeholder needs, continuous improvement through regular assessments, employee involvement in problem-solving, and a process approach that optimizes each project phase. Addressing these gaps and embracing proactive quality improvement measures early during the planning stage and before issuing the projects for bidding, JSWP can

enhance efficiency, reduce waste, and deliver high-quality outcomes that meet or exceed client expectations.

The Role of Artificial Intelligence in Quality Management

Artificial intelligence has emerged as a promising solution to address the complexities and challenges faced while implementing effective quality management systems in the construction industry. AI-powered technologies offer a range of capabilities that can streamline quality management processes and enhance project outcomes. Some studies identified some drivers for AI adoption such as cost, time, performance and customer satisfaction, which are directly related to project outcomes (Yang et al., 2019). Other studies listed some possible benefits of AI such as automating inspections and improving accuracy to leveraging predictive analytics to identify potential issues, AI aligns well with quality management principles and can help construction organizations overcome the inherent difficulties in implementing robust quality management systems (Cubric, 2020).

Recent studies have highlighted several ways AI can enhance quality management in construction. Key technologies like Building Information Modelling (BIM), augmented reality (AR), Internet of Things (IoT), and computer vision (CV) are being integrated into CQM processes (Abioye et al., 2021). AI's success in optimizing manufacturing, healthcare, and finance processes offers strong evidence of its transformative power across industries. Therefore, AI has a high potential in the construction industry by demonstrating how AI can automate inspection processes, identify potential issues, and improve decision-making (Datta, S. D et al., 2024; Nagireddy, 2023).

The case study by Makaula et. al. (2021) highlights the transformative potential of AI in construction project management through the development of a framework that integrates AI technologies across various phases of the project lifecycle. It emphasizes AI's role in enhancing planning, design, execution, and material sourcing while addressing critical aspects such as labor productivity and risk management. This framework is particularly relevant to the current study, as it provides a structured approach to applying AI in construction quality management, emphasizing how AI

can optimize processes, improve decision-making, and mitigate project risks. Moreover, the study identifies key challenges to AI adoption, such as high costs and resistance due to job security concerns, which align with barriers faced in the Saudi construction industry.

In the context of JSWP, similar challenges are encountered across the program's large-scale and complex projects. The phased nature of JSWP, coupled with recurring issues in quality planning, inspection, and material management, underscores the need for an AI-driven framework to address inefficiencies. By leveraging AI tools to streamline workflows, enhance compliance monitoring, and proactively manage risks, JSWP can achieve better project outcomes while aligning with Saudi Vision 2030's goals for innovation and sustainability.

However, the construction industry faces persistent challenges in adopting digital technologies. Issues like low productivity, frequent rework, and cost overruns (Pan & Zhang, 2021) highlight the lag in digitalization and the untapped potential of AI. By integrating AI as a moderating variable in quality management practices, construction projects can achieve more consistent and reliable quality outcomes, meeting the industry's evolving demands and paving the way for sustainable advancements.

This study will investigate the impact and outcomes of AI-driven technologies, including automation and predictive analytics, on construction quality management. Prominent AI platforms such as Google ML, Microsoft Azure, and IBM Watson offer relevant AI-powered solutions that merit further exploration and analysis within this research context. These platforms offer AI Technology, such ML and NLP, which can support transformative construction quality management practices.

Automation of Quality Processes

One of the key areas where AI can enhance quality management in construction is through automated quality control and inspection. AI-powered computer vision and machine learning algorithms can be leveraged for automated quality inspections, detecting defects, and monitoring construction progress (Regona et al., 2022). AI technology improves the accuracy and consistency of inspections and reduces manual

effort and time required, enabling construction teams to identify and address quality issues proactively. For example, AI-driven visual inspection systems can analyze site photographs or video footage to identify deviations from design specifications, detect structural defects, or monitor the installation of building components (Hooda et al., 2021; Luo et al., 2022).

Previous research by Pan & Zhang (2021) has shown that computer vision has increasingly supplanted labor-intensive and often inconsistent visual inspections in evaluating the state of civil infrastructure. This technology enables automated detection of damage, recognition of structural components, identification of unsafe behaviors, and assessment of overall conditions. Such applications of AI in quality control and inspection processes in infrastructure projects can significantly enhance efficiency, accuracy, and timeliness in addressing quality-related issues by facilitating monitoring applications through non-contact methods, capturing a quantitative understanding of infrastructure status, such as estimating strain, displacement, and measuring crack length and width.

Identifying and predicting quality issues

The ability of AI to predict potential quality issues is a transformative application in construction quality management. By analyzing historical project data, real-time sensor inputs, environmental factors, and supply chain disruptions, AI-powered predictive models can forecast quality problems such as delays, cost overruns, defects, or equipment failures (Abioye et al., 2021). For instance, machine learning techniques, as demonstrated in recent research by Dip Datta et al. (2024), have proven effective in identifying construction risks by considering factors like project complexity, weather conditions, and supply chain uncertainties.

Additionally, AI can support informed decision-making in quality management by providing predictive insights and actionable recommendations. By processing vast amounts of data from past projects, real-time site conditions, and process information, AI systems can identify trends, suggest optimal actions, and highlight areas of concern. Similarly, findings by Sota (2017) on AI in construction planning emphasize the potential of AI-driven tools to optimize planning processes by analyzing historical

data, forecasting risks, and automating decision-making to improve project outcomes. These capabilities align with the principles of Quality Planning, which focus on defining objectives, allocating resources, and identifying potential risks to prevent defects. The integration of AI's decision-support systems enables project teams to make more accurate and timely decisions, improving resource allocation, reducing inefficiencies, and enhancing overall project quality (Dabous et al., 2023).

For large-scale Programs like JSWP, AI's predictive capabilities are instrumental in tackling persistent issues such as utility conflicts, material issues, non-compliance to procedures, and project delays. By analyzing historical and real-time data and utilizing predictive analytics, AI empowers project teams to foresee potential risks and implement solutions before problems arise. This preventive approach reduces the likelihood of rework, minimizes disruptions, and curbs additional costs. Furthermore, AI enhances coordination across the program's numerous sites, ensuring smoother workflows and higher-quality outcomes. Incorporating AI-powered predictive tools into quality management practices allows construction projects to achieve their quality objectives more effectively, leading to improved performance greater project success and customer satisfaction.

Improving the efficiency of quality management processes

AI-powered technologies can also enhance the efficiency and effectiveness of quality management in construction by automating routine tasks, streamlining data collection and analysis, and optimizing quality control workflows. AI techniques can also generate valuable insights into the complex construction process. This knowledge is critical to project success and can guide the optimization of the construction execution process, helping to make the project run more smoothly and efficiently (Pan & Zhang, 2021). For instance, AI-driven natural language processing can automate the extraction and analysis of quality-related information from project documentation, such as inspection reports, checklists, and requests for information.

Another way to enhance construction quality management processes is by integrating artificial intelligence with existing quality management tools and methodologies, such as Failure Mode and Effects Analysis (FMEA), Statistical Process Control (SPC), and

Lean Quality Management Systems, to improve their effectiveness (Yang et al., 2019). AI-based Integrated Quality Management Information System (IQMIS) proposed by Yang et al. (2019) enables real-time data acquisition, predictive modeling, and intelligent decision-making across quality planning, control, and improvement. For example, AI can link FMEA data with IoT devices or other systems to better manage, monitor, and optimize quality-related processes throughout the construction lifecycle. These innovations allow established QMS to proactively identify and address quality risks, reduce inefficiencies, and improve overall project outcomes.

The reliance on traditional inspection methods in JSWP poses significant challenges in managing quality across the program's large and complex projects. With numerous dispersed sites, high volumes of activities, and intricate interdependencies, traditional approaches often fail to provide the scalability and real-time responsiveness needed to ensure consistent quality. These limitations result in delayed identification of defects, inefficient allocation of resources, increased rework, and increased extension of time requests. Integrating AI technologies into the quality management process can bridge these gaps by automating inspections, analyzing data in real-time, and predicting potential quality issues before they escalate. By transitioning from reactive to proactive quality management, AI can enhance the efficiency and effectiveness of CQM practices, ensuring better outcomes for large-scale and complex infrastructure projects like JSWP.

Challenges in Adopting AI in Construction Quality Management

A recent pilot survey conducted to explore the adoption of artificial intelligence in Saudi Arabia's construction industry provides valuable insights into the sector's awareness, readiness, and challenges regarding AI integration. The survey revealed a range of barriers, including limited technical expertise, insufficient data quality, and resistance to change, as well as concerns over job displacement and high implementation costs. Additionally, regulatory uncertainties and the lack of clear frameworks for AI adoption were highlighted as significant hurdles.

These findings offer a snapshot of the industry's current landscape and emphasize the need for targeted strategies to address both technical and organizational challenges. These insights are particularly relevant to this study, as they underscore the importance of preparing the industry for AI-driven solutions.

While the potential benefits of AI in construction quality management are significant, there are also several challenges and barriers to widespread adoption. Adopting AI-powered technologies in construction quality management contexts can be improved by factors such as the industry's traditional resistance to change, concerns over data privacy and security, the need for upfront investment in new technologies, and AI-specific skills and expertise among construction professionals. (Regona *et al.*, 2022).

Cultural, Social, and Organizational Challenges: The lack of adherence to organizational QMS and established CQM practices poses significant barriers to successfully integrating AI technologies in the construction industry. This challenge is particularly evident in JSWP, where frequent non-compliance with quality procedures undermines the effectiveness of quality management systems. Similar challenges are observed in studies like Khan *et al.* (2019), which identified insufficient adherence to QMS standards, lack of training, and inconsistent enforcement of quality protocols as critical obstacles. These issues are further exacerbated by cultural and organizational resistance to change, coupled with a lack of commitment to quality, which disrupts the implementation of structured quality processes.

Moreover, social and organizational challenges significantly hinder the adoption of AI-driven quality management practices in the construction industry. Concerns about job security, resistance to change, and the steep learning curve associated with new technologies are prevalent among construction professionals (Regona *et. al.*, 2022). The Saudi construction industry remains deeply rooted in traditional practices, where quality management systems are often not perceived as a strategic priority. Aichouni *et al.* (2014) emphasized similar challenges in their study on the Hail region, where insufficient training, lack of top management commitment to quality, and organizational resistance were identified as critical barriers to the effective implementation of quality management systems. These challenges have perpetuated

widespread non-adherence to QMS practices, further limiting the industry's ability to adopt advanced AI-driven quality solutions.

Many organizations, including JSWP, view quality management as an additional administrative burden that increases costs and delays work progress rather than as an essential investment for achieving long-term success. This mindset perpetuates a cycle of low adoption of modern quality management frameworks, making it difficult for companies to recognize the significant benefits these systems can bring, such as enhanced efficiency, reduced rework, improved customer satisfaction, and better reputational standing within the industry (Quadri et. al. 2021).

AI technologies depend on structured and reliable processes to deliver meaningful insights and operational benefits. However, foundational gaps in quality management, combined with social and cultural barriers, result in flawed data and workflows that diminish the value of AI applications (Westenberger et al., 2021). These challenges align closely with the first Research Question, which examines how CQM practices become insufficient in addressing the complexities of large-scale infrastructure projects. Without addressing foundational gaps in quality culture, such as ensuring adherence to standards and fostering accountability, AI solutions are unlikely to deliver their intended benefits. This highlights the urgent need for management intervention to instill a robust quality culture within the organization.

Integration with Existing Systems: Integrating AI systems with existing quality management processes can be complex and often requires high technical expertise. Successful integration demands careful planning to ensure that AI tools complement existing workflows rather than disrupt them. This challenge is particularly evident in construction projects, where established procedures and legacy systems may need to be adapted or updated to accommodate new AI-driven approaches (Na et al., 2023; Jäkel et al., 2022).

Data Quality and Availability: The effectiveness of AI technologies in construction heavily depends on the quality and availability of data and the expertise of professionals managing these systems. Reliable and relevant data are essential for

training AI models to provide accurate predictions and insights. However, construction projects often face challenges such as data variability, incomplete records, and inconsistent data collection practices, which hinder the development of robust AI applications (Castronuevo & Arboleda, 2024; Kelepouris, 2023).

Skill Gap: The skill gap presents a significant barrier to AI adoption in the construction industry, with a shortage of trained professionals limiting the ability to develop, implement, and manage AI systems effectively (Castronuevo & Arboleda, 2024). This challenge is further compounded by organizational issues, including insufficient stakeholder alignment, trust and resistance to change, which hinder the seamless integration of AI technologies (Cubric, 2020). In the context of JSWP, these barriers are particularly evident, as the program relies on fragmented quality management frameworks and traditional methods. Bridging the skill gap requires substantial investment in targeted training and education programs to equip personnel with the expertise needed to leverage AI technologies effectively. Addressing these foundational requirements, including high-quality data and skilled expertise, and management support is essential for successfully integrating AI into Construction CQM practices and achieving improved project outcomes.

Ethical Considerations: Nagireddy (2023) and Cubric (2020) indicated that using AI in various business sectors, including construction, raises important ethical considerations that must be carefully addressed. Issues such as trust, data privacy, algorithmic bias, and the potential displacement of human workers by non-human system, are critical concerns that must be proactively managed. For example, ensuring the protection of sensitive project data and mitigating biases in AI-powered decision-making processes are essential to maintain trust and fairness in AI applications.

Additionally, the potential impact of AI on construction workers, such as job automation, should be considered and balanced with the need for technological advancements. Adopting a human-centered approach that prioritizes ethical principles, such as transparency, accountability, and employee well-being, is crucial for AI's successful and responsible integration in construction quality management.

Careful consideration of these ethical factors will help foster trust, acceptance, and the equitable deployment of AI-driven solutions in the industry (Abioye et al., 2021).

Cost of AI integration: The benefits of AI-driven solutions in the construction industry are indisputable. Several researchers, including Luca et al. (2022), Abioye et al. (2021), and Sota (2017), found that the initial investment and ongoing maintenance costs of AI-driven solutions, such as robotics or CV can be prohibitively high, particularly for small-scale subcontractors and firms that comprise a significant portion of the construction industry. This poses a significant barrier to the widespread adoption of these technologies. Therefore, Luca et al. (2022) discussed deeper the cost-benefit challenge of AI adoption and emphasized the need for construction companies to invest in data collection and processing technologies to utilize AI effectively. They also pointed out that companies should focus on clear target areas for AI implementation rather than simply adopting the latest technology trends without a precise cost-benefit analysis. This suggests that the initial cost of AI and the associated data infrastructure is challenging for broader adoption in the construction industry.

Construction companies will face additional challenges when traditional and manual construction quality management practices are already in place, which is the case in JSWP. Integrating AI-driven solutions will require significant changes to existing processes and workflows, and construction firms may be reluctant to abandon their established quality management approaches, even if AI offers potential benefits. Cubric (2020) suggested the use of hybrid solutions combining AI and non-AI systems. Overcoming this resistance to change and ensuring a smooth transition to AI-enabled CQM will be a critical challenge that construction companies must address.

This study argues that integrating artificial intelligence in construction quality management holds significant potential to enhance project outcomes. Nevertheless, researchers have identified that addressing the challenges associated with AI adoption is essential to fully realizing its benefits. Investing in training and education,

establishing industry standards, and proactively tackling ethical considerations will be pivotal to successfully integrating AI-driven solutions in the construction industry.

Construction Projects outcomes

Various factors, including project management practices, resource availability, environmental conditions, stakeholder involvement, and organizational culture, influence construction project outcomes. Most research studies concur that key project outcomes in construction are typically evaluated using the Iron Triangle of Project Management, encompassing cost, schedule, and quality, along with additional factors such as Scope, safety, customer satisfaction, environmental compliance, and legal adherence (Teshome & Gobana, 2018; Leong et al., 2014). These metrics are broadly recognized as vital indicators of project success, offering a holistic assessment of a project's performance and alignment with stakeholder expectations and prevailing industry standards.

Cost

Cost is a fundamental measure of construction project success. Effective cost management, including accurate budgeting, cost control, and efficient resource utilization, is crucial for ensuring projects are completed within the allocated budget (Leong et al., 2014). Previous studies have highlighted the significant impact of cost overruns on project profitability, client satisfaction, and the overall viability of construction firms. Also explored the negative impacts of cost overruns on various aspects of construction projects. Neyestani, B. (2016) concluded on his research that effective QMS can positively impact time performance and cost control, leading to better project outcomes.

While high-quality design might initially increase costs, ensuring conformance to quality standards during construction can lead to long-term cost savings. On the other hand, poor-quality construction can result in significant long-term problems, including structural issues, safety hazards, and costly repairs (Tang et al., 2005.). Similarly, robust quality management practices, like AI-Driven, require upfront investment, but the costs of rework and remedying defects often exceed these expenses. The study by Ali et. al. (2010) emphasizes the importance of prevention,

appraisal, and failure costs in improving project outcomes but notes significant barriers, such as poor knowledge and limited resources, which hinder effective implementation. Additionally, poor quality can undermine customer satisfaction, damage a company's reputation, and lead to legal liabilities. Ultimately, the long-term consequences of substandard quality outweigh any short-term cost savings, emphasizing the critical importance of effective quality management in construction projects.

Schedule

Timely project delivery is another crucial measure of construction project success. Time performance evaluates the project's adherence to its planned Schedule. Delays in construction projects can lead to significant financial losses, missed business opportunities, and reputational damage for construction firms. The study by Hwang and Yang (2014) highlights rework as a major contributor to project delays, with its root causes often tied to quality-related issues such as design errors, inadequate quality control, and poor adherence to project specifications. The research underscores the importance of proactive quality management in minimizing rework, noting that early identification and resolution of potential quality issues can significantly reduce disruptions and improve project schedules. By addressing rework at its root, through robust quality assurance and control practices, construction projects can enhance efficiency and achieve better outcomes.

Low & Ong (2014) suggest that integrating quality management practices, such as comprehensive quality planning, quality assurance, and quality control, can help mitigate schedule delays and improve overall time performance in construction projects. For JSWP, adopting robust quality management practices would provide a more structured approach to addressing quality-related inefficiencies. By emphasizing quality planning and assurance, the program could proactively identify and mitigate risks that contribute to delays, ultimately improving time performance across its large and complex infrastructure project.

The survey conducted by Assaf & Al-Hejji (2006) identified numerous factors contributing to schedule delays in the construction industry in Saudi Arabia, including

poor planning, ineffective subcontractor management, material shortages, adverse weather conditions, and change orders. Similar issues have been observed in JSWP, particularly poor planning and delayed design approvals, which exacerbate schedule delays across the program's dispersed and concurrent projects. Additionally, poor quality, defects, and reworks further compound these delays, disrupting workflows and increasing the time required to complete projects.

The studies discussed highlight rework as a significant contributor to project delays, often stemming from quality-related issues such as design errors, inadequate quality control, and poor compliance with project specifications. These findings emphasize the critical need for proactive quality management practices, as rework not only disrupts workflows but also escalates costs and prolongs schedules. In the context of JSWP, rework is particularly impactful given the program's scale and complexity. Issues such as delayed design approvals and non-compliance with quality plans exacerbate schedule delays, creating ripple effects across the program's dispersed and concurrent projects. Addressing these challenges requires robust quality assurance and control practices that prevent rework by ensuring adherence to specifications and early detection of quality issues, ultimately improving time performance.

Quality

Quality is one of the three dimensions of the Iron Triangle and serves as a critical measure of construction project success. In the context of construction, quality refers to the conformance of the final product or service to specified requirements, standards, and client expectations. This definition aligns with the principles of Philip Crosby, who emphasized that "quality is conformance to requirements." Quality performance is assessed by evaluating the quality of workmanship, materials, and adherence to established specifications and standards, ensuring that the constructed facility meets or exceeds stakeholder expectations (Crosby, 1980).

Poor quality in construction can have far-reaching consequences, including structural failures, safety hazards, client dissatisfaction, and legal liabilities. The construction industry has long struggled with quality issues, and research suggests that most quality-related problems are attributed to the human factor, particularly a need for

more professional ethics and commitment to quality for all stakeholders involved in the project (Aziz, 2013). To address this challenge, construction firms have increasingly adopted various quality management frameworks, such as Total Quality Management, Six Sigma, and Lean Construction, to improve quality assurance and control throughout the project lifecycle.

However, the adoption of quality management frameworks has faced significant challenges in the construction industry. Despite the potential benefits, construction firms need help effectively implement and sustain these practices throughout the project lifecycle. Lack of employee buy-in, resistance to change, and the complex, fragmented nature of construction projects has hindered the widespread adoption and success of these quality management initiatives (Aichouni et al., 2014) (Srdoč et al., 2005). Moreover, the construction industry's traditional focus on time and cost, often at the expense of quality, has contributed to the persistent quality issues faced by the sector (Jraisat et al., 2016).

In the context of the Jeddah Stormwater Program, the expansion of projects in size and complexity has led to a noticeable rise in the number of Site Observation Reports (SORs) and Non-Conformance Reports (NCRs). These reports highlight recurring issues such as deviations from approved designs, inadequate compliance with quality standards, material issues, non-adherence to quality plan, and defects arising during construction. The growing volume of SORs and NCRs underscores the challenges of maintaining consistent quality control across a program of this scale, further emphasizing the need for more efficient and proactive quality management practices. Integrating AI-driven technologies could help reduce such occurrences by automating compliance checks, enhancing real-time monitoring, and identifying potential quality issues before they escalate. This would provide a systematic approach to managing quality in large-scale infrastructure projects like JSWP.

Customer Satisfaction

Customer satisfaction is an essential measure of construction project success, as it reflects the extent to which the client's expectations and requirements are met. This is particularly important in the construction industry, where projects are often highly customized and tailored to the client's needs.

Various factors influence customer satisfaction, including the quality of the final product, the timeliness of project delivery, and overall responsiveness and communication throughout the construction process. In the construction industry, client satisfaction is a multidimensional concept encompassing various aspects, such as project delivery, quality of workmanship, timeliness, responsiveness to issues, and overall project experience (Alshihre et al., 2020). Achieving high levels of customer satisfaction is crucial for construction firms, as it can lead to repeat business, positive word-of-mouth referrals, and improved reputation within the industry. Moreover, satisfied clients are more likely to be willing to engage in collaborative partnerships and support future projects, which can be particularly beneficial in the highly competitive construction market (Ramlee et al., 2016).

Conclusion of Literature

The literature highlights several methods for measuring construction project outcomes, focusing on traditional metrics and the potential for AI to enhance measurement accuracy and efficiency (Leong et al., 2014). AI-powered technologies offer transformative opportunities in quality management, such as automating inspections, predicting quality issues, and improving workflow efficiency. However, existing quality research often applies AI to isolated aspects of quality management or specific project outcomes, without addressing its holistic, systematic impact on overall CQM practices (Dabous et al., 2023).

The literature table at the end of this chapter provides a structured review of key themes in the study. The first section examines the challenges associated with traditional Construction Quality Management practices, particularly in large and complex projects. This section highlights recurring issues such as non-compliance with quality standards, defect detection, and rework management, which are prevalent

in infrastructure projects. Numerous case studies within this section provide valuable insights into these challenges, reinforcing the widespread nature of these problems across various contexts.

In contrast, the second section focuses on the intersection of Quality Management and Artificial Intelligence. This review identifies a notable gap in existing literature, where studies primarily focus on isolated applications, such as predictive analytics or defect detection, without exploring AI's systemic impact on CQM as an integrated framework. Moreover, there is a lack of case studies examining the practical implementation of AI in enhancing CQM practices. This gap highlights the need for this study for further investigation into AI's role in optimizing quality planning, control, assurance, and improvement.

The third section explores AI applications in construction and project management, emphasizing its ability to optimize specific outcomes, such as cost or schedule performance. However, these studies often overlook AI's broader potential to revolutionize quality management practices holistically. Together, these insights underline the necessity for a comprehensive investigation into AI's transformative role in CQM, which this study aims to address. By focusing on the Jeddah Stormwater Program as a case study, this research seeks to bridge this gap and offer a novel contribution to the field.

<u>No</u>	<u>Title</u>	<u>Author</u>	<u>Year</u>	<u>Literature Summary</u>	<u>Researcher Comments and relevance to JSWP</u>
A	Literature related to Quality Management and Project / Construction management - Challenges of Traditional CQM Practices				
A01	Quality management at construction projects case study of stormwater network project (Case Study - UAE)	Hamdan	2024	This paper highlights the implementation of quality management systems in stormwater network projects. It emphasizes the importance of strict adherence to QMS processes during all stages of work to prevent defects, ensure compliance, and reduce rework. Specific examples of quality violations and corrective actions are provided from the conducted case study.	The paper provides valuable insights into quality management challenges and corrective measures in a stormwater context, offering parallels to JSWP's recurring quality issues such as MOS, ITP and shop drawings, and opportunities for AI-driven solutions.
A02	Quality Assurance and Quality Control for Project Effectiveness in Construction and Management	Salvi & Kerkar	2020	The paper examines the importance of QA and QC in enhancing project effectiveness within the construction industry. The study emphasizes that defects or failures in constructed facilities can lead to increased costs and delays, making QA/QC crucial for ensuring uniformity and compliance with specifications. The authors outline the methods of implementing QA/QC processes, such as inspections, documentation, and adherence to standards, highlighting how these measures can improve project quality and reduce costs over the project lifecycle	This paper provides valuable insights into how QA and QC practices contribute to project outcomes such as cost efficiency, quality consistency, and stakeholder satisfaction , which are key areas of focus of the thesis on quality management's impact on construction project outcomes. The paper also outlined the challenges and benefits of QA/QC integration, offering context on how these practices might be further enhanced through AI technologies in complex projects like the Jeddah Stormwater Program.
A03	Evaluation of Quality during construction projects (Case study – Pakistan)	Khan et. al	2019	In this study, the authors Identifies major challenges in QMS implementation, including insufficient adherence to standards, lack of training, and inconsistent enforcement. Cultural & organizational resistance further hinders adoption.	Highlights non-compliance with existing CQM practices, similar to JSWP, emphasizing the need to address foundational issues before integrating AI into quality management systems.
A04	Framework to Enhance the Implementation of Quality Management System in Construction (Case Study – Malaysia)	Othman et. al	2018	The study Identifies challenges in implementing QMS in high rise construction, including limited QA/QC knowledge, poor worker attitudes, high material waste, and excessive QA/QC workloads. Proposes a framework emphasizing management commitment and resource optimization.	The authors Highlight similar challenges with JSWP, such as non-compliance to quality procedures and inefficiencies in supervision. Provides a foundational framework to complement AI-driven CQM solutions for large infrastructure projects.

<u>No</u>	<u>Title</u>	<u>Author</u>	<u>Year</u>	<u>Literature Summary</u>	<u>Researcher Comments and relevance to JSWP</u>
A05	Critical Success Factors in Infrastructure Projects: A Case Study of Flood Mitigation (Case Study – Malaysia)	Zakaria et al	2017	In this study, the authors identify critical success factors for infrastructure projects “Stormwater” like planning, stakeholder coordination, and adherence to master plans in flood mitigation projects. Highlights resource allocation and compliance as barriers.	The study Offers insights into JSWP challenges by emphasizing planning, compliance, and coordination gaps, which challenge traditional CQM practices and support the demand for AI integration in CQM.
A06	Quality in construction management: an exploratory study	Jraisat et al.	2016	This paper investigated the factors that affect quality in construction. It highlighted the construction industry’s focus on cost and time at the expense of quality, leading to persistent issues.	The paper found that the major factors affecting quality in construction are human resource management, customer satisfaction, and construction related issues.
A07	Effectiveness of Quality Management System (QMS) on Construction Projects	Neyestani	2016	This paper evaluated the impact of QMS implementation in construction projects. It found that QMS can affect customer satisfaction, cost, time, and quality. The findings emphasize that QMS implementation enhances project outcomes by systematically improving management processes. AI can further improve decision-making by providing data-driven insights, predictive analytics, and real-time feedback loops	Although the paper investigates the broader effects of QMS, including customer satisfaction and operational efficiencies, it particularly notes that QMS least affects the project scope or quality compared to other factors. This gap suggests that while QMS frameworks (like ISO 9001) standardize processes, there might be room for enhancing their direct impact on quality, which is where AI could play a transformative role and can be integrated into QMS to amplify its effectiveness, especially quality management.
A08	Rework and schedule performance: A profile of incidence, impact, causes and solutions	Hwang & Yang	2014	This paper investigated the effect of reworks on projects. It was found that rework is a significant factor in schedule delays with a high occurrence rate. Root causes of reworks include design changes and poor design coordination.	Rework often arises from inadequate planning and poor coordination among stakeholders, compounded by frequent non-compliance with procedures, delays in Method Statements (MOS), and shop-drawing approvals caused by change orders. The study explores the impact of rework on both schedule and cost, highlighting its disruptive effects on project performance. Integrating AI into quality management systems could help minimize rework and enhance schedule adherence. By automating elements of the change management process and utilizing predictive analytics, AI could proactively identify potential schedule or budget overruns related to rework and mitigate their impact.

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A09	The Degree of Using Methods of Quality Management in the Implementation of Construction Projects in Jordan	Khatatbeh, Ahmed	2014	The study highlighted varying levels of implementation of CQM practices in the construction industry in Jordan. The study listed the most significant problems that hinder the application of CQM practices such as management commitment, effective communication between stakeholders, lack of staff training and others. The challenges impact on the ability of construction companies to meet the required quality and customers needs.	The result of the study aligns with JSWP challenges, such as non-compliance with quality protocols and weak organizational alignment, lack of adequate supervision, stakeholders' coordination, emphasizing the need for foundational improvements to enable AI integration in CQM.
A10	An empirical study of quality management systems in the Saudi construction industry (Case Study – KSA)	Aichouni et al.	2014	The study highlights significant challenges in implementing Quality Management Systems (QMS) in the Saudi construction industry in Hail Region, focusing on insufficient training, lack of top management commitment, and organizational resistance. These issues result in widespread non-adherence to QMS strategies, tools, and techniques, particularly in the Hail region.	This study emphasizes how foundational gaps in QMS implementation, such as poor adherence to quality processes and organizational resistance, make the adoption of advanced AI-driven solutions even more challenging. This is directly applicable to JSWP, where similar non-compliance and adherence issues exacerbate the complexity of integrating AI technologies.
A11	Project Quality Management Critical Success Factors for Buildings (IMP)	Low, S. P., & Ong, J	2014	This book explores how effective quality management practices influence the success of projects. The authors identify critical success factors such as leadership commitment, stakeholder engagement, continuous improvement, and adherence to standards. Using case studies, they illustrate strategies for integrating quality management systems, emphasizing customer satisfaction and risk.	The author emphasizes leadership, stakeholder engagement, continuous improvement, and adherence to standards directly ties into the core areas of Quality Planning, Quality Control, Quality Assurance, and Quality Improvement . Also, his perspective for examining how structured quality practices impact project outcomes such as cost, schedule, quality, and customer satisfaction goes well with the aim of the thesis
A12	Study of Quality Management in Construction projects	Chin Keng, Hamzah	2011	The article highlights that quality management should be intertwined with all operational and managerial processes within a construction company. It emphasizes the need for a strong management commitment to quality, the implementation of appropriate quality management practices, and addressing the challenges that hinder effective quality management in construction projects	The findings of this paper highlighted the importance of quality management in construction projects. The author highlighted that quality management in construction is not stand alone management, which support the importance of CQM practices as it the role of every one on the project.

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A13	Quality Cost in the Construction Industry – Preliminary Findings in Malaysia (Case Study – Malaysia)	Ali, et. al.	2010	Explores the awareness and application of Cost of Quality (COQ) principles in construction. Highlight challenges such as poor knowledge, limited resources, focus on short-term profits over preventive measures. Suggests COQ as performance indicator for continual improvement to ISO9001	The study emphasizes COQ as a tool to address JSWP challenges by reducing costs and inefficiencies. Proposes leveraging AI to optimize COQ processes, enhance resource allocation, and minimize rework.
A14	Factors Affecting the Performance Of Construction Projects In The Gaza Strip (Case Study – Gaza)	Enshassi et al.	2009	The paper identifies several key factors impacting construction project performance in the Gaza Strip, including delays due to border and road closures leading to material shortages, unavailability of resources, escalation of material prices, and the lack of experienced personnel. These issues highlight the complex interplay between external economic and political conditions and internal project management challenges.	the paper does not specifically focus on AI, the challenges it outlines—like resource availability, material cost escalation, and effective project leadership—can be mitigated through AI technologies. AI can predict material shortages or optimize resource allocation, enhancing project performance. conformance to specifications and quality of equipment and materials. AI tools can enhance quality assurance processes, ensuring compliance and improving the overall material management system. This approach is part of the objectives of this research.
A15	A Case Study on Quality Management System in Construction Project (KLIA) (Case Study – Malaysia)	Abdullah et. al.	2008	Highlights challenges in implementing QMS for the Kuala Lumpur International Airport project (KLIA), including integrating PQPs, stakeholder coordination, and compliance with statutory and project-specific standards. Emphasizes the importance of structured approaches like inspections, testing, and audits.	The study's emphasis on auditing, inspection, and testing aligns with the JSWP's identified needs. For example, KLIA's method of integrating inspection and testing plans (ITP) into PQPs can be highlighted as a best practice that JSWP could adopt, especially when integrated with AI technologies to automate and monitor compliance in real-time. It also mirrors JSWP's challenges in managing compliance and coordination across dispersed projects. Suggests AI as a tool to automate monitoring and enhance compliance management.
A16	The Role of Culture as Driver of Quality Management and Performance: Infrastructure Versus Core Quality Practices	Naor et al.	2008	The study investigated the relationships between organizational culture, infrastructure, core quality management practice, and the link to performance. It provides an insightful exploration of how organizational culture influences quality management practices and overall performance. The study distinguishes between infrastructure and core quality management practices and analyzes their interactions with organizational culture in the context of manufacturing performance.	These findings can be directly relevant to this research by illustrating the crucial role of cultural factors in the implementation and effectiveness of quality management practices in construction projects. The research can find out how similar dynamics apply within the Jeddah Stormwater Program and other construction contexts, particularly how AI can be integrated to enhance these interactions and outcomes.

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A17	Quality Assurance and Control in the Construction of Infrastructure Services in Developing Countries (Case Study – Pakistan)	Khan et al.	2008	The authors examined the challenges and implementation of quality assurance & quality control practices in construction. The study highlights the importance of CQM practices and to apply it, including lack of clear specifications, limited stakeholder awareness, and inadequate statistical methods. Highlights the potential of computer-aided tools to enhance QA/QC processes.	This study Highlights similar CQM challenges in JSWP, that are also affected by the size and complexity of construction projects, emphasizing the need for AI-driven solutions to improve compliance and efficiency of CQM practices.
A18	Causes of delays in large construction projects (Case study – KSA)	Assaf & Al-Hejji	2006	The author conducted a survey on time performance of different types of construction projects in Sadu Arabia. The survey aimed to find out the cause of delay in construction. It found that average of 10% to 30% of deviation from original schedule. 70% of projects had overrun, and the major cause was changing orders.	The author identified poor planning, ineffective subcontractor management, and material shortages as significant challenges to quality management. All these issues directly related to current challenges we are facing at JSWP

B	Literature related to Quality Management and Artificial Intelligence – AI in Enhancing Quality management				
B01	A Literature Review of Artificial Intelligence in Asphalt Quality Assurance (Case Study)	Ryan B. Castronuevo Edwin R. Arboleda	2024	Reviews AI applications in asphalt quality assurance, highlighting intelligent sensing aggregates, machine learning for defect detection, and dynamic monitoring systems. These innovations enhance quality evaluation, decision-making, and material optimization.	This study provides a relevant example of how AI-driven quality management systems can improve construction project outcomes. It can provide a model for integrating AI into quality management processes in large-scale projects. For JSWP, AI could enhance compliance monitoring, automate quality checks, and proactively address defects. The study also highlights challenges related to data availability and model interpretability, offering insights into potential limitations and considerations when adopting AI-driven solutions in complex construction projects.
B02	Editorial: Automation and artificial intelligence in construction and management of civil infrastructure	<i>Dabous et al.</i>	2023	discusses the increasing trend of automation and AI adoption in the construction industry. It highlights the slower pace of adopting new technologies in construction compared to other sectors due to the industry's complexity.	This Demonstrated the use of predictive analytics to identify and mitigate quality risks, such as delays and cost overruns. The author emphasizes the need for more research to understand the potential of AI and automation in addressing construction and management challenges, which is in light with the focus of the current research

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B03	Digital technology for quality management in construction: A review and future research directions	Luo et al.	2022	The research investigated digital- technology that can be used to enhance CQM. Results found enhancement in detecting concealed works and preventive and post-completed defects.	This paper focuses on digital technologies in quality management, including use of AI. It provides a clear connection between digital technology apps and the enhancement of quality management processes illustrating both current capabilities and gaps in technology application within the scope of construction quality management, highlighting opportunities, but not relating those benefits to project outcomes.
B04	Failure of AI Projects: Understanding the Critical Factors	Westenberger et. al	2021	The paper Identifies factors contributing to AI project failures, including unrealistic expectations, organizational constraints, and technological challenges like poor data quality and model instability.	Highlight barriers relevant to JSWP, such as resistance to technology, lack of skilled personnel, and data challenges, which must be addressed for successful AI integration in CQM.
B05	Drivers, Barriers, and Social Considerations for AI Adoption in Business and Management	Maria Cubric	2020	The author identifies a significant skill gap in AI adoption due to a lack of trained professionals and discusses organizational challenges, such as resistance to change and insufficient stakeholder alignment.	Highlights the need for addressing skill gaps and organizational barriers in JSWP, emphasizing the importance of training and alignment for AI integration into CQM practices.
B06	Artificial Intelligence for Product Quality Inspection toward Smart Industries: Quality Control of Vehicle Non-Conformities	Chouchene et al	2020	The paper discusses the integration of AI within smart factory systems and how it overcomes limitations of manual inspection, such as operator fatigue and inconsistency, by using AI-driven automation and cognitive capabilities. and the use of AI-based vision systems to improve product quality inspection in smart industries, particularly for the detection of non-conformities in vehicles. The proposed system leverages AI, specifically machine vision (MV), to automate defect detection and minimize human error in inspection tasks	The paper shows how AI-driven systems can improve quality inspection processes by enhancing accuracy, reducing errors, and increasing productivity—concepts that can be adapted to the construction industry, particularly for complex infrastructure projects. Automated detection can ensure quality control aligns with the focus on how AI can enhance quality management practices and optimize project outcomes. Insights from this paper can support the exploration of how AI technology can transform traditional quality assurance and control methods into more data-driven, efficient systems.
B07	Imaging Quality Control in the Era of Artificial Intelligence	Larson and Boland	2019	This paper discusses how AI technologies can transform quality control in medical imaging. The authors outline eight key elements essential for comprehensive process control in AI-based imaging systems, emphasize that AI tools alone cannot guarantee consistent quality without integrating these essential process control elements.	This paper might be on the medical field, but the concepts might apply on defect detection on construction projects, especially on material delivery inspection. The idea will need future investigation.

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B08	Integrating AI Technologies in Quality Management Systems	Yang et al.	2019	The paper tried to discover the connection between QMS and AI tech by exploring how AI enhanced quality tools help in improving predictive analytics can enhance decision-making in quality management processes. A conceptual framework of AI based Information Quality Management System “IQMIS” framework was developed, to enhance QMS functions.	This study is directly applicable to JSWP, as we are trying to understand the effect of AI-enhanced QMS tools such as predictive analytics to monitor ongoing projects and anticipate risks.
B09	Models and Methods for Quality Management based on AI application	Srdoc et al.	2005	The paper presents a comprehensive approach to enhancing quality management through AI-driven techniques by leveraging AI technologies such as text mining, aspect sentiment analysis, and decision tree modeling to evaluate and improve customer satisfaction. The approach emphasizes using big data to monitor and evaluate service quality continuously, thus supporting more dynamic and effective decision-making in quality management.	The paper studied how AI can be leveraged to analyze large volumes of data and transform customer feedback into actionable insights, thereby improving overall project quality and customer satisfaction. It may provide useful frameworks or inspiration for incorporating AI-driven decision support in JSWP. This could help demonstrate how AI tools can enhance data-driven decision-making, using big data tech, i.e. historic data from previous projects.

C	Literature related to Artificial Intelligence and Project / Construction Management				
C01	Artificial intelligence and machine learning applications in the project lifecycle of the industry: A comprehensive review	Datta, S D et al	2024	The paper thoroughly assesses how AI and ML can be effectively integrated across various phases of a construction project's life cycle. Also, how AI and ML can revolutionize the construction industry by enhancing productivity, reducing cost overruns, improving site safety, and optimizing project management efficiency.	The paper did not mention the use of AI in quality planning during the planning stage of the project. Also, the lack of focused investigation into how AI can enhance quality management practices in construction provides a unique angle for the study.
C02	Artificial Intelligence and Its Impacts on Project Management	Reddy Nagireddy, Sindhu	2023	The paper investigated how AI can be integrated into PM practices, concluding that AI can improve project planning, resource allocation, risk management, and decision-making.	AI tools can improve the accuracy of forecasting, perform repetitive tasks, and enhance decision-making through predictive analytics and data-driven insight. But it did not address the explicit connection between AI technologies and their direct impacts on quality management in construction projects.

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C03	A Qualitative Study on Artificial Intelligence and Its Impact on the Project Schedule, Cost and Risk Management Knowledge Areas Presented in PMBOK®	Friðgeirsson et al.	2023	This paper focuses on the impact of AI on PMBOK's area of knowledge, cost, risk, and schedule. The research shows that AI has potential benefits in these areas, particularly where historical data and repeated tasks are involved	The implications of AI in cost, risk, and schedule management could indirectly influence quality management by improving overall project control and precision, which are essential for maintaining quality standards. Showing a gap in studying how to integrate AI into CQM
C04	Investigating AI Applications in Construction Industry: A Systematic Review	Seyman-Güray, T	2023	This study examined AI's contributions to handling challenges in the construction industry, such as cost overruns, delay, risk, rework, and safety issues. The construction industry's characteristic resistance to new technologies is noted as it is among the least digitized sectors.	This paper provides a broad overview of AI's application in the industry. There is considerable potential for transformative impacts through AI in project monitoring, and enhanced decision-making, but does not focus deeply on quality management practices, emphasizing the gap in direct studies linking AI with CQM in construction projects.
C05	Mapping Two Decades of AI in Construction Research: A Scientometric Analysis from the Sustainability and Construction Phases Lenses	Regina et al.	2023	The paper investigated the effect of AI technology on improving sustainability, productivity, and efficiency. AI technologies such as machine learning, deep learning, and big data can affect construction projects' performance and digitize and modernize the construction industry, consolidating its processes and practices toward a more sustainable future.	The study suggests a growing trend towards integrating AI more comprehensively across all construction phases and deeper into sustainability practices. It provides broad understanding of how AI is applied in the industry but does not focus on quality management, and encourages ongoing innovation and research to overcome existing barriers to AI adoption in construction
C06	A Comprehensive Literature Review of Research Trends of Applying AI to Construction Project Management	Merdžanović et al.	2023	This research investigated how AI affects construction project management, including planning, scheduling, monitoring, execution, and controlling. It emphasizes how AI can automate routine tasks, improve decision-making through data analytics, and optimize project outcomes by enhancing efficiency and accuracy.	This paper provides a foundational understanding of AI's impact on construction project management but does not delve deeply into quality management practices. While it covers AI's role in enhancing project efficiency and decision-making, the direct effects on quality management are not specifically addressed, which presents a gap.
C07	Adoption of Artificial Intelligence for Optimum Productivity in the Construction Industry	Victor	2022	This study focused on bridging the gap between AI and its advantages in the construction industry by reviewing several case studies. It also explores how AI and people should interact and the degree of human trust in AI technology.	The paper emphasizes AI's role in automating processes, improving efficiency, and aligning with lean principles, which prioritize reducing waste and increasing value. A significant part of the study discusses the level of trust between humans and AI systems as a critical factor for successful AI integration.

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C08	An investigation into the Impact of Artificial Intelligence on the Future of Project Management	Alshaikhi & Khayyat	2021	This paper discussed the effect of using AI in PM; it highlights several AI tools and applications that could support project managers by automating tasks and providing analytical insights, thus improving the overall management of projects. However, it was found that AI can automate tasks but cannot replace human minutes or decrease the need for human resources.	The paper provides insights into how AI could be leveraged to automate and optimize project management tasks, which could extend to quality management practices in construction. The paper acknowledges several challenges in implementing AI in project management that require attention in future research, such as data availability, integration difficulties, high costs, and the potential impact on employment due to automation.
C09	Roles of artificial intelligence in construction engineering and management: A critical review and future trends. Automation in Construction	Pan & Zhang	2021	The study notes a shift in focus from traditional expert systems to more advanced technologies like BIM, smart robotics, cloud VR/AR, IoT, digital twins, 4D printing, and blockchain technologies. The study found AI can benefit the construction industry in terms of automation, risk mitigation, high efficiency, digitalization, and computer vision. Challenges in adoption include data quality issues, integration complexities, and investment in new technologies.	This paper directly addresses the broad applications of AI in construction but does not focus specifically on quality management. It explored AI-powered technologies to automate inspections and improve decision-making in quality control workflows. It can provides a solid foundation for understanding how AI technologies are currently used and how they can potentially transform the industry. This research will focus specifically on how AI can improve quality management practices within construction projects
C10	Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges	Abioye et al.	2021	The study explored AI applications in CE, identifying opportunities and challenges for adoption. It explored the benefits of using several AI technologies, such as CV, robotics, NLP, ML, etc. The paper offers a critical review of existing AI applications across various construction activities, highlighting how AI is being used to tackle complex problems & enhance efficiency in construction management.	AI technology uses predictive analytics, such as forecasting project delays or optimizing resource allocation and automated construction processes, enhancing precision and safety on sites. it outlines the potential and challenges of AI in construction, which can be directly relevant to this research focus on enhancing quality management through AI. However, the paper does not explore the impact on quality management practices.
C11	Impact of Artificial Intelligence on the South African Construction Project Management Industry (Case Study)	Makaula et al.	2021	In this practical study the author develops a framework for applying AI in construction management across the project lifecycle. It highlights how AI can support planning, design, execution, and material sourcing while addressing labor productivity and risk management. It also identifies potential barriers, such as high costs and job security concerns.	The paper offers insights into AI's practical applications and barriers in construction, providing a comparative foundation for exploring AI integration within JSWP. Highlights specific lifecycle areas that could benefit from AI adoption which aligns with the focus of the research Juran quality tribology. However, it doesn't specifically focus on quality management practices, which provides an opportunity for this research to delve deeper into this aspect, particularly how AI can be integrated to enhance quality management in construction projects.

<u>No</u>	<u>Title</u>	<u>Author</u>	<u>Year</u>	<u>Literature Summary</u>	<u>Researcher Comments and relevance to JSWP</u>
C12	Artificial Intelligence for Product Quality Inspection toward Smart Industries: Quality Control of Vehicle Non-Conformities	Chouchene et al.	2020	This work proposes an automated artificial vision system leveraging AI to detect vehicle defects, aligning with the principles of Industry 4.0. Additionally, a brief review of AI-based quality control methods highlights the challenges of Visual Inspection (VI) and demonstrates AI's effectiveness, particularly in vehicle manufacturing industries.	In this paper the author proposed an Intelligent Quality Management Information System (IQMIS) for real-time monitoring and optimization of quality processes in the car manufacturing industry. This approach can be insightful for developing a framework of AI-driven CQM practices for JSWP.
C13	The Effect of Using Artificial Intelligence on the Quality of Decision-Making in Various Organizations: A Critical Survey Study	El-Emary et al.	2020	The study aimed to investigate the impact of AI on the quality of decision-making in various types of organizations. The results showed a positive impact despite the organization's structure. It also discussed popular techniques and algorithms of artificial intelligence.	The paper provides a critical analysis of existing research, highlighting the use of various AI techniques like Neural Networks, Support Vector Machines, and Bayesian Networks to enhance decision-making accuracy and efficiency. Such an approach can be used in assessing and analyzing the data for the case study.
C14	Research on the Application of Intelligent Construction Site in Construction Site Management	Zhang, M	2020	This paper investigated the use of intelligent construction sites (information tech) to manage construction sites more efficiently, focusing on quality and safety problems by integrating information technologies like BIM, IoT, and cloud computing in construction management.	The paper provides evidence of how AI and related technologies can be utilized to minimize quality and safety issues, and the use of BIM technology to predict potential problems and improve communication among construction site personnel. However, the paper didn't link the positive impact of AI on safety and quality on project outcomes.

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