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Letter of Acceptance

Dear Author: Ismail Ujaimi ,Rabab Alsaigh ,Majid Alfelfel, Raed Algallaf

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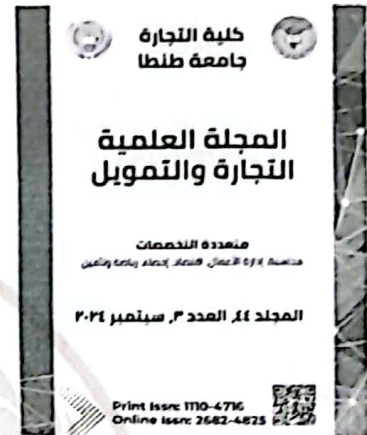
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8 أغسطس 2024

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قسم المحاسبة، كلية الإدارة، جامعة ميدأوشن، الفجيرة، الإمارات

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Research Paper Publication Acceptance Letter

Dear Ismail Ujaimi, Rabab Alsaigh

Greetings,

Based on the review of your research entitled:

"The Limitations of Traditional Construction Quality Management in Large-Scale
Infrastructure Projects in Saudi Arabia"

we are pleased to inform you that your research has been accepted for publication according to the evaluations of the esteemed reviewers. It will be published in *Midocean Journal for Research and Studies*, issued by Midocean University - The Comoros Islands.

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"Adoption of Artificial Intelligence in the Construction Industry in Saudi Arabia: Challenges and Proposed Solutions"

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ABSTRACT: This paper examines the integration of Artificial Intelligence (AI) within the Saudi Arabian construction industry, addressing key challenges, potential solutions, and its transformative potential. With Saudi Arabia's Vision 2030 emphasizing technological innovation and economic diversification, the construction sector stands to benefit significantly from AI-driven advancements that improve productivity and enhance project management. Key challenges identified include technical barriers, such as data quality issues, complex system integration, and the limited availability of specialized AI tools. Additionally, regulatory hurdles related to compliance and data privacy, high implementation costs, limited ROI, and social resistance driven by job displacement fears and lack of AI familiarity pose significant obstacles.

A survey conducted among industry professionals confirmed these challenges, highlighting difficulties in AI system integration, economic concerns about costs and talent shortages, and regulatory uncertainties. Social resistance to AI adoption also emerged as a critical barrier, underscoring the need for workforce training and change management strategies to foster acceptance. The paper proposes targeted solutions, including improving data integration capabilities, establishing comprehensive regulatory frameworks, providing financial incentives, and offering training programs to build AI-related expertise.

Case studies and hypothetical scenarios illustrate AI's potential benefits, such as optimizing resource allocation, enhancing safety, reducing costs, and streamlining project timelines. Government-backed initiatives like King Salman Energy Park (SPARK) emphasize the importance of infrastructure and state support in facilitating AI adoption across industries. These efforts align with national goals to transform construction practices and drive innovation.

The findings demonstrate AI's potential to revolutionize the construction sector, but overcoming existing challenges requires continuous collaboration between industry stakeholders, policymakers, and technology providers. Further research is necessary to validate these assumptions and explore practical strategies for AI integration, ultimately paving the way for a more efficient, innovative, and sustainable construction industry.

KEYWORDS: Artificial Intelligence (AI) in Construction, Saudi Construction Industry, AI Integration in Saudi Projects, Vision 2030 Saudi Arabia, AI Adoption Challenges

1. INTRODUCTION

AI is revolutionizing industries by automating processes, improving decision-making, and driving innovation in sectors like healthcare, finance, and construction, leading to increased efficiency, accuracy, and productivity (Merdžanović, Vukomanović, & Ivandić Vidović, 2023).

1.1 Understanding Artificial Intelligence

AI enables machines to mimic human intelligence, performing tasks like decision-making and problem-solving (Phaladi et al., 2022). In construction, AI integrates technologies such as machine learning and robotics, allowing machines to simulate human-like thinking and assist in complex project tasks (Altaie & Dishar, 2024).

1.2 AI's Significance in Global Industries

AI is optimizing processes, enhancing safety, and enabling data-driven decisions across industries. In project management, it improves scheduling, risk prediction, and resource allocation (Krishnan & Krishnan, 2024). In construction, AI automates planning, design, and monitoring, increasing efficiency and reducing errors (Zabala-Vargas et al., 2023).

1.3 AI in the Construction Industry

The construction industry, typically recognized for its labor-intensive nature and high-risk conditions, has recently started integrating AI to enhance project outcomes. AI applications in construction span areas such as project scheduling, safety monitoring, quality control, and cost estimation. By utilizing AI, the construction sector is becoming increasingly data-driven, employing predictive models to foresee potential challenges, simplify processes, and minimize both time and expenses.

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1.4 Project Planning and Management

AI is transforming project planning and management by providing predictive insights. By analyzing historical data, including weather patterns, AI tools offer valuable foresight for efficient scheduling and resource allocation (Merdžanović et al., 2023), reducing delays and enhancing decision-making.

1.5 Enhanced Learning and Skill Development

In South Africa, AI is improving construction workforce development by identifying skill gaps, suggesting training, and enhancing competencies (Phaladi et al., 2022). This is particularly valuable in developing regions where skills shortages impact project efficiency.

1.6 Knowledge Management Integration

Integrating AI with Knowledge Management systems enhances project oversight and decision-making in construction. These systems capture, organize, and share knowledge, fostering collaboration and efficient information sharing (Altaie & Dishar, 2024), leading to improved project execution and risk mitigation through real-time information and predictive analytics.

1.7 Automation and Robotics in Construction

AI-powered robotics are transforming construction by automating tasks like bricklaying and welding, improving safety, and reducing reliance on manual labor (Krishnan & Krishnan, 2024). This automation enhances productivity and shortens project timelines.

2. CASE STUDIES OF AI APPLICATION IN CONSTRUCTION

2.1 Application of Big Data and AI in Project Life Cycle Management

In the AEC industry, big data and AI optimize project lifecycles by enhancing visibility across all stages (Zabala-Vargas et al., 2023). This technology analyzes vast datasets to streamline resource allocation, improve quality control, and predict outcomes, reducing costs and time.

2.2 AI in Safety Monitoring and Risk Management

AI significantly contributes to construction safety by using predictive models to assess risks based on environmental factors, worker behavior, and equipment conditions (Merdžanović et al., 2023). This proactive approach minimizes accidents, ensures compliance with safety standards, and enhances project outcomes.

2.3 Improving Project Delivery and Quality Control

Research shows that AI applications, including machine learning, enhance project delivery by automating quality checks and overseeing task schedules (Krishnan & Krishnan, 2024). With real-time data analysis capabilities, AI enables managers to monitor project performance, anticipate possible delays, and make prompt adjustments, thereby maintaining quality control.

3. CHALLENGES AND FUTURE PROSPECTS

Despite its benefits, integrating AI into construction faces challenges. High implementation costs, a lack of skilled professionals, and resistance to technological change are significant barriers (Altaie & Dishar, 2024). Concerns also exist regarding data privacy and ethical AI use, especially given the sensitive data involved in construction projects.

AI's role in construction is expected to expand significantly. Advancements in digital twin technology, IoT, and blockchain will enhance data management and security, leading to increased productivity, cost-effectiveness, and improved project outcomes as more companies adopt AI (Zabala-Vargas et al., 2023).

4. ASSUMPTIONS AND HYPOTHESES

Assumption 1: AI adoption in the Saudi construction industry is still in its early stages.

Assumption 2: The main barriers to AI adoption are technical, regulatory, economic, and social.

Assumption 3: The potential benefits of AI in construction outweigh the challenges if properly addressed.

5. THEORETICAL BACKGROUND

The adoption of artificial intelligence (AI) in the architecture, engineering, and construction (AEC) industry has gained significant momentum in recent years. AI applications have demonstrated potential in several areas, including architectural design, site logistics planning, safety management, progress monitoring, productivity improvement, and building operations and maintenance. Technologies like machine learning and computer vision have shown increasing applicability to construction-related tasks, enabling automation and enhanced decision-making (Regona et al., 2022). These advancements are not just theoretical; they provide tangible benefits which make AI a valuable tool for transforming traditional construction workflows.

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Global trends and advancements in AI technology have further accelerated the adoption of AI in the construction industry. Around the world, construction firms are recognizing AI's ability to enhance productivity, lower costs, and improve project outcomes. Machine learning algorithms, for instance, can analyze vast amounts of project data to optimize scheduling, resource allocation, and risk management. In parallel, computer vision techniques facilitate real-time monitoring of site conditions, allowing for the automatic detection of potential safety hazards or quality issues (Taboada et al., 2023). Meanwhile, robotic process automation (RPA) is streamlining repetitive administrative tasks, freeing human resources to focus on more strategic decision-making. Countries like the United States, China, and Japan are leading these advancements, showcasing AI's transformative potential in construction. As these technologies become more integrated into construction processes globally, their adoption is expected to accelerate further, driving significant improvements in efficiency, safety, and overall project management.

Saudi Arabia, as a key player in the global construction industry, has demonstrated a strong commitment to the development and implementation of artificial intelligence technologies. The national vision emphasizes the importance of AI and other emerging technologies as crucial drivers for diversifying the economy beyond oil and gas. Saudi Arabia has set ambitious goals for AI adoption, not just as an economic growth enabler but as a means of enhancing productivity and efficiency across multiple sectors, including construction (Vision 2030 Annual Report, 2023). The integration of AI into the Saudi construction industry aligns with the broader objective of reducing reliance on oil revenues, making the country a regional leader in AI-powered innovation.

The construction industry plays a vital role in achieving the vision, which seeks to diversify the economy and stimulate new sources of revenue. Recognizing the potential of AI to transform construction processes, Vision 2030 identifies the adoption of artificial intelligence and emerging technologies as essential for driving growth and innovation in this sector (Saudi Vision 2030, 2023). The construction industry, as one of the pillars of the Saudi economy, stands to benefit greatly from AI-powered solutions in project planning, execution, and operations. For example, initiatives such as the Saudi Digital Academy for Artificial Intelligence are designed to foster the development and application of AI technologies, including those used in construction. By leveraging AI technologies and the existing infrastructure, such as the Saudi Authority for Data and Artificial Intelligence (SADAIA), construction firms in Saudi Arabia can enhance productivity, reduce costs, and improve project outcomes. (can we cite our first paper here?). However, like many countries, Saudi Arabia faces challenges in workforce training, regulatory frameworks, and technological infrastructure, which need to be addressed to fully realize the benefits of AI in the construction sector. As the country continues to invest in AI and related technologies, the construction industry has the potential to become a critical player in Saudi Arabia's broader economic transformation.

6. ASSUMED CHALLENGES IN USING AI IN THE SAUDI CONSTRUCTION INDUSTRY

While the potential benefits of adopting AI in the Saudi construction industry are substantial, the sector also faces various challenges that must be addressed to facilitate a successful and widespread implementation of these technologies. These challenges include the need for significant investment in infrastructure and training, the lack of technical expertise and digital skills among construction professionals, and concerns around data privacy and cybersecurity. Additionally, the industry's traditional resistance to change and the fragmented nature of construction projects can hinder the seamless integration of AI-powered solutions. Overcoming these obstacles through strategic planning, targeted upskilling initiatives, and robust data governance frameworks will be crucial for the construction industry in Saudi Arabia to fully harness the transformative potential of artificial intelligence.

6.1 Technical Challenges

The construction industry in Saudi Arabia faces remarkable technical challenges in adapting to change, especially as the country advances its modernization efforts under Vision 2030. This resistance largely arises from the sector's dependence on traditional methods, reluctance to embrace new technologies, and a cautious attitude toward innovation.

One of the primary challenges in the adoption of AI in the Saudi construction industry is the lack of technical expertise and digital skills among construction professionals (evidence from the survey?). Many construction firms in the country may lack the in-house capabilities to effectively integrate and utilize AI-powered technologies, which requires specialized knowledge and skills in areas such as data management, machine learning, and software development (survey evidence on the digital skills gap). Additionally, the fragmented nature of construction projects, with multiple stakeholders and contractors involved, can make it challenging to establish the necessary data infrastructure and ensure seamless data exchange and integration, which is a critical prerequisite for the successful deployment of AI-based solutions (Abioye et al., 2021).

Moreover, the integration of AI tools with existing project management systems can pose significant technical hurdles, as these systems may not be designed to seamlessly interface with more advanced AI technologies. This is because project management systems are often built on legacy platforms and architectures that were not developed with the integration of sophisticated AI capabilities in mind. Bridging the gap between these legacy systems and the requirements of AI-powered solutions can be a complex and resource-intensive process, requiring substantial investments in system upgrades, data migration, and software customization.

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(need reference here). Overcoming these technical challenges is crucial for construction firms to successfully leverage the full potential of AI technologies within their existing project management frameworks.

(Mahmood et al., 2023) "Including artificial intelligence is an essential involvement in managing projects as new technologies are arising and depending on old style tools and techniques will no longer work for new complex projects".

Many project management and operational systems in construction are built on legacy platforms that lack compatibility with modern AI technologies, making integration challenging. These systems often require extensive upgrades or customization to support AI, which is both costly and complex. **Weng. (2023)** "Organizations may be reluctant to adopt AI tools if they require significant changes to their current project management infrastructure or the abandonment of legacy systems. This can result in hesitance to embrace AI-driven project management solutions, even if they offer significant benefits in terms of efficiency and decision-making support". Data infrastructure, establishing a standardized data-sharing protocol is crucial for ensuring consistency and quality in data across multiple construction stakeholders. Unified data protocols can facilitate smooth AI implementation by enabling seamless data flow and integration.

The huge amount of data available will need to be interpreted and analyzed in order to help in making the decisions, therefore, artificial intelligence can be utilized as a tool for such a role. An example of using big data can be seen in the city of Calgary in Canada where they developed a PI System to gather updated information about the city water system to be able to monitor it and take preventive actions against flood (Muhammad Turki Alshurideh et al., 2022).

technology's capability to act by human judgment is questioned. Humans apply discrete language and descriptive terminology in diverse fields of practice. Experts of the discipline need to be trained in AI technology. Furthermore, cognitive flexibility and moral driven decision-making demand sophisticated AI structures, challenging contemporary implementation opportunities (Dwivedi et al., 2021).

Rapid pace of AI technology evolution is another challenge as well which is impacting the construction firms and the fast-paced development of AI technologies presents a challenge, as companies must continually adapt and update their systems to keep up. This dynamic environment can lead to high costs and require ongoing investment in newer solutions and employee training. **Weng. (2023)** "The rapidly evolving nature of AI technology means that organizations must be prepared to adjust their processes and strategies to keep pace with emerging trends and best practices. This ongoing process of adaptation can be resource-intensive and may require organizations to be agile and open to change"

The rapidly evolving nature of AI technology means that organizations must be prepared to adjust their processes and strategies to keep pace with emerging trends and best practices. This ongoing process of adaptation can be resource-intensive and may require organizations to be agile and open to change.

6.2 Regulatory and Legal Challenges (Ethical Consideration)

Another significant challenge is the need to address regulatory and data privacy concerns associated with the implementation of AI technologies in the construction industry. Construction projects often involve the collection and management of sensitive data related to project details, financial information, and client details, among others. Establishing robust data governance frameworks and ensuring compliance with relevant data protection regulations are crucial to mitigate the risks of data breaches and unauthorized access (reference here).

Ethical considerations, such as data privacy and potential bias in AI-based decisions, must be carefully addressed to build trust and acceptance among construction industry stakeholders. Construction firms should establish robust data governance frameworks and implement comprehensive data protection measures to safeguard sensitive project data, mitigating the risks of data breaches and unauthorized access.

Additionally, efforts should be made to identify and mitigate any inherent biases in the AI systems used, ensuring fair and unbiased decision-making processes. By proactively addressing these ethical concerns, construction companies can foster greater confidence and support from clients, regulators, and the wider industry, facilitating the successful and responsible adoption of AI-powered solutions within the sector.

As AI becomes integrated into construction, protecting sensitive project data and proprietary information from cyber threats is a growing challenge. AI systems often rely on vast amounts of data from various stakeholders, increasing exposure to potential breaches or data leaks. Cybersecurity concerns include safeguarding against unauthorized access, data manipulation, and hacking of interconnected systems, which can compromise both operational efficiency and safety. Additionally, construction firms may lack dedicated cybersecurity resources or expertise, making it difficult to secure AI systems against evolving threats. Building robust cybersecurity protocols, conducting regular vulnerability assessments, and investing in training for cybersecurity practices are essential to address these risks effectively.

Weng. (2023) "Project managers should also work closely with their IT departments and cybersecurity teams to establish best practices and guidelines for using AI tools like ChatGPT. Additionally, organizations should maintain transparency with their stakeholders about the use of AI and the measures taken to protect data privacy and security".

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Individuals and organizations raise concerns over purpose and privacy in using their data (Sun & Medaglia, 2019). Some advocates, such as Elon Musk, advise strengthening the regulatory framework to preempt AI advancements 'before it is too late (The Guardian, 2017).

Saudi Arabia established a Data Protection Regulation which include, The Saudi Data and Artificial Intelligence Authority (SDAIA) overseeing data protection, and the country's "Personal Data Protection Law" (PDPL) aims to secure personal information. Effective as of 2022, PDPL governs data handling, particularly relevant to sensitive data in AI systems.

6.3 Economic Challenges

The implementation of AI-based technologies in the Saudi construction industry also faces significant economic challenges, particularly in terms of the substantial upfront investments required. Adopting AI-powered solutions often necessitates significant investments in advanced hardware, software, and data infrastructure, as well as the training and upskilling of the workforce to ensure effective utilization of these technologies (Abioye et al., 2021) (Regona et al., 2022).

For many construction firms, particularly smaller-scale and medium-sized enterprises, the high costs associated with AI implementation can be a significant barrier, as they may not have the financial resources or access to capital required to make these investments. Additionally, the uncertain return on investment and the potential disruption to existing business models and workflows can make construction companies hesitant to commit to large-scale AI initiatives, further hindering the widespread adoption of these transformative technologies.

Khayyat M. & Alshaikhi A. (2021). "Adoption and implementation of AI are not so easy to develop due to expensive operation costs and equipment". Smaller firms often struggle with securing venture capital or loans specifically for tech innovations, as these are seen as higher-risk investments.

Dwivedi et al. (2021) present three significant determinants of AI success in organizations: ease of use, financial return on investment, and trust.

Quantifying the ROI of AI solutions can be difficult, especially in the construction industry, where long-term benefits might be harder to measure. Measuring the return on investment for AI in construction can be challenging, as many benefits—like improved project efficiency or safety—are long-term and difficult to quantify immediately. (Bughin et al., 2018). "AI's significant economic challenges to organizations and institutions address the required investments for technology and changes in contemporary working practices. Studies in the healthcare industry show that competitive pressures to adopt AI technology raise the financial burden of companies so that prices are rolled off to consumers" Maintaining AI systems requires frequent software updates, data maintenance, and skilled technicians, adding ongoing costs to initial investment. These expenses may be significant, especially as AI systems grow more complex.

6.4 Social Challenges

Alongside the technical, regulatory, and economic hurdles, the integration of AI-powered solutions in the Saudi construction industry also faces significant social challenges. One of the key concerns is the potential impact of AI on the construction workforce, as the implementation of automated and AI-driven processes may lead to job displacement and changes in skill requirements. Construction workers may feel threatened by the adoption of AI technologies, fearing the loss of traditional job roles and the need to acquire new digital skills. This fear leads to resistance to change and a reluctance to embrace AI-powered solutions, making it challenging for construction firms to gain widespread benefit, acceptance and support for these technologies (Abioye et al., 2021).

Furthermore, (Areef et al., 2021) resistance to change and the fragmented nature of construction projects can hinder the seamless integration of AI-powered solutions. Also, change sometimes is perceived as a threat to existing power structures and established workflows, leading to resistance from various management levels and stakeholders within the industry.

Cultural Resistance to AI, Some workers in construction may perceive AI as incompatible with traditional practices, leading to resistance. Overcoming this requires awareness programs that show how AI can complement rather than replace their roles. Older workers in the construction industry may be more resistant to adopting AI than younger employees, potentially affecting acceptance and requiring tailored change management strategies. **Weng. (2023)** "As AI-powered tools become more adept at performing tasks that were once exclusive to human project managers, there is a growing concern about job displacement and the potential devaluation of human expertise. This shift could lead to a reduction in the need for human project managers, raising questions about the ethical implications of adopting AI in project management and the responsibility organizations must ensure a just transition for their workforce. Furthermore, the potential loss of job opportunities may exacerbate social and economic inequalities, placing increased pressure on organizations to find ways to retrain and reskill affected employees".

In addition to the challenges caused by potential unemployment, some researchers predict the exclusive interaction between machines and humans through automation and robotization to cause mental disorders and other psychiatric issues (Ashrafiyan, 2017; Wright & Schultz, 2018). Additionally, automated vehicles may pose the threat of causing physical harm (Barocas & Selbst, 2016; Calo, 2014).

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7. ASSUMED SOLUTIONS

Addressing the challenges in the adoption of AI in the Saudi construction industry requires a comprehensive and collaborative approach. Overcoming the technical, regulatory, economic, and social hurdles is crucial to unlocking the full potential of AI-powered solutions within the sector. Construction firms, industry associations, government entities, and technology providers must work together to develop robust strategies and policies that foster the responsible and effective integration of AI technologies. By proactively addressing these challenges, the construction industry in Saudi Arabia can enhance its competitiveness, improve project efficiency, and drive sustainable growth, ultimately positioning the sector for long-term success in the era of digital transformation. Some proposed solutions to the challenges include:

7.1 Technical Solutions

Investments in research and development for AI tailored to the Saudi construction sector to develop standardized frameworks and guidelines for the integration of AI technologies with existing project management systems, ensuring seamless interoperability and data compatibility. Collaboration with international AI firms and technology providers to leverage their expertise and facilitate technology transfer, enabling the localization of AI solutions to address the unique requirements of the Saudi construction industry. Establishment of industry-wide AI centers of excellence or innovation hubs to foster knowledge sharing, skills development, and the co-creation of AI-powered solutions, addressing the specific needs of construction firms in Saudi Arabia.

Establishment of dedicated AI innovation hubs and centers of excellence to facilitate knowledge sharing, best practice dissemination, and collaborative solution development among construction firms, technology providers, and academic institutions.

Khayyat M. & Alshaikhi A. (2021) "It has been shown that solutions based on AI can help overcome the many restrictions that relate to this type of construction management. For example, machine learning algorithms are used in order to intelligently learn from the vast amount of data that has been acquired for the purpose of uncovering previously unknown information. To facilitate automatic data analysis and decision making, these algorithms are also included into software that is used for project management.

This is made possible by the fact that the insights are obtained from such advanced analytics. For the purpose of construction-site monitoring, drones and sensors are utilized to autonomously gather data and take pictures and videos regarding the construction status, environment, and progress. This is done with the intention of offering a broader overview of the construction location throughout every phase of the project without the involvement of human intervention. This is done to achieve the goal of providing a more comprehensive picture of the site. Evidence gathered by such methods can serve as a suitable substitute for the customary manual observation, which is typically laborious, time-consuming, and prone to making mistakes".

7.2 Regulatory and Legal Solutions (Ethical Consideration)

Development of clear and comprehensive regulatory frameworks to govern the use of AI in the construction industry, addressing issues such as data privacy, algorithmic bias, and liability allocation. Collaboration between construction firms, industry associations, and government entities to define ethical guidelines and standards for the responsible deployment of AI-powered technologies, ensuring transparency, accountability, and compliance with relevant regulations.

Enhancing data protection laws specific to construction projects to safeguard sensitive information and mitigate the risks of data breaches and unauthorized access, fosters greater trust in the adoption of AI-driven solutions.

Ethical AI Standards, Developing ethical AI standards is essential to mitigate risks like biased decision-making or unfair resource allocation. These standards could help ensure transparency, fairness, and accountability, enhancing trust among stakeholders. Various aspects highlight the ethical criticality in AI. First, intelligent agents may exhibit discrimination caused by biases in programming or data input. Second, many AI algorithms cannot reason upon their outputs. Third, the long-term impacts of the technology are yet polarizing. Hence, the current regulatory framework is advocated to swiftly adapt to current AI challenges (Duan et al., 2019; Dwivedi et al., 2021).

Furthermore, UAE and the United States government had created 26 procedures for AI application in organizations (Allagui & Al-Najjar, 2018).

7.3 Economic Solutions

Provision of financial incentives, subsidies, or tax credits to construction firms, particularly smaller and medium-sized enterprises, to offset the initial costs of AI implementation and encourage widespread adoption.

Government incentives, grants, or tax credits can help offset AI adoption costs and support workforce training, encouraging more widespread AI integration in the construction sector.

Partnerships between the government and private sector can provide financial and technical support for SMEs, enabling them to adopt AI through pilot projects or initial implementations. (Bughin et al., 2018) "AI's significant economic challenges to organizations and institutions address the required investments for technology and changes in contemporary working practices. Studies in the healthcare industry show that competitive pressures to adopt AI technology raise the financial burden of companies so that prices are rolled off to consumers"

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7.4 Social Solutions

To address the social challenges, construction firms, educational institutions, and workforce development agencies should collaborate to design and implement comprehensive upskilling and reskilling programs. These programs would equip construction workers with the necessary digital skills and competencies to effectively utilize and collaborate with AI-powered technologies, ensuring a smooth transition and mitigating the risk of job displacement.

Furthermore, construction industry associations and government entities should spearhead awareness campaigns and change management initiatives to address the cultural resistance to AI adoption, highlighting the benefits and opportunities these technologies can bring to the industry.

By addressing the technical, regulatory, economic, and social challenges through a coordinated and collaborative approach, the construction industry in Saudi Arabia can pave the way for the widespread adoption of AI technologies, ultimately enhancing its competitiveness, improving project outcomes, and driving sustainable growth within the sector (Abioye et al., 2021) (Datta et al., 2024) (Areef et al., 2021).

Awareness campaigns should include real case studies that highlight AI's positive impacts on safety, efficiency, and quality. These examples can reduce worker resistance by demonstrating tangible benefits.

Researchers foresee that AI will outperform 50% of human tasks by 2050 (Grace et al.,

2018). The substantial erosion of jobs (Ford, 2013; Pueyo, 2018) could potentially cause increased divergence in social welfare (Eubanks, 2018) since AI is to replace rather lower-paid repetitive jobs (Huang et al., 2019). Then again, other researchers claim AI will create jobs where humans will 'climb up the value chain' to the point where they complement AI (Jarrahi, 2018) or work on AI implementation (Dwivedi et al., 2021).

8. CASE STUDY SCENARIOS

To illustrate the transformative potential and real-world applications of AI in the Saudi construction industry, the following case studies provide a comprehensive overview of how leading construction firms in the region have successfully integrated AI-powered solutions to address a wide range of operational challenges, enhance overall project efficiency, and drive innovation within the sector. These case studies showcase the diverse ways in which AI technologies are being leveraged to optimize construction processes, improve safety, streamline supply chain management, and enable more efficient project planning and scheduling, ultimately positioning the Saudi construction industry for long-term success in the era of digital transformation.

8.1 First Case Study: AI-Powered Project Planning and Scheduling

Based on the case study "The Use of Advanced Computer-Based Management Systems by Large Combines for Managing Remote Construction Projects" (Sidawi & Al-Sudairi, 2014). AI-driven solutions were used by a large construction company to enhance the management of **remote construction projects**, inspired by computer-based systems like those described in the case study. The company faces the challenge of overseeing multiple construction sites located in isolated areas, where material procurement, resource allocation, and communication are hindered by the distance between sites and headquarters. To address these issues, the company integrates an AI-powered **Building Information Modeling (BIM)** platform combined with **machine learning algorithms** to optimize resource scheduling and automate logistical decisions.

8.1.1 AI Implementation

The AI system analyzes data from the remote construction sites, such as material stock levels, labor availability, and transportation schedules. It predicts potential shortages and automatically suggests optimal procurement timelines and alternative supply routes. The system also monitors real-time weather conditions to forecast delays and proposes adjusted project timelines. Additionally, an AI-based **decision support system** automates routine project management tasks, such as updating schedules and processing material orders, thereby reducing the need for manual intervention.

8.1.2 Challenges Faced

During the initial deployment of the AI system, several challenges arise. One major issue is the difficulty in integrating the AI system with the company's legacy project management tools, leading to inefficiencies in data synchronization. Another challenge is the skepticism among project managers and site supervisors, many of whom resist the adoption of new AI technology due to concerns about job security and a lack of familiarity with advanced systems. Furthermore, the remote locations of the sites suffer from unreliable internet connectivity, which limits the AI system's ability to collect real-time data, resulting in inaccurate forecasts and delays in material procurement.

8.1.3 How Challenges Were Addressed

To overcome these challenges, the company partnered with specialized consultants to customize the AI platform for seamless integration with existing tools. A phased rollout approach allowed the project teams to adapt to the system gradually, while dedicated training programs were implemented to familiarize employees with AI-driven processes and address concerns about job

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displacement. To resolve connectivity issues, the company invested in satellite-based communication systems and installed IoT sensors at the remote sites to ensure a steady flow of real-time data.

8.1.4 Outcomes

Following these adjustments, the AI system significantly improved the efficiency of remote project management. Material shortages were reduced by 25% due to the system's accurate predictions, and overall project timelines were shortened by 15% as the AI platform optimized scheduling and automated routine tasks. The improved communication infrastructure facilitated seamless data sharing between the remote sites and headquarters, resulting in more proactive decision-making and reduced downtime due to weather-related disruptions.

8.2 Second Case Study: AI-Enabled Safety Monitoring

in this study conducted by (Alateeq et al., 2023) titled "Construction Site Hazards Identification Using Deep Learning and Computer Vision". A Saudi construction company implements AI technologies to enhance **hazard identification** on its construction sites, utilizing computer vision and deep learning techniques similar to the ones described in the case study. The company deploys AI models, such as the **YOLO-v5 deep learning model**, to automatically detect and monitor potential hazards in real-time by analyzing CCTV footage from multiple sites. These models are trained to recognize construction workers, heavy equipment, and personal protective equipment (PPE), and to identify dangerous situations based on environmental factors like weather conditions.

8.2.1 AI Implementation

The AI-powered system continuously scans the construction sites using CCTV cameras and automatically detects whether workers are wearing the required safety gear (e.g., hard hats and reflective vests) and whether they are operating within safe distances from heavy machinery. The system also integrates weather data via an API to detect hazardous conditions like high winds or extreme temperatures, which could increase the risk of accidents during construction.

8.2.2 Challenges Faced

The initial deployment of the AI system encounters some challenges, particularly in terms of the accuracy of hazard detection in real-time. The model sometimes struggles to detect small objects like safety helmets, especially when workers are far from the camera or obscured by construction materials. Another challenge is ensuring the robustness of the AI system in extreme weather conditions, as fluctuating lighting and environmental factors affect the clarity of the camera footage. Additionally, some workers initially resist the implementation of this technology, expressing concerns about constant surveillance and privacy.

8.2.3 How Challenges Were Addressed

To improve the accuracy of hazard detection, the company enhances the training datasets with additional images captured under varying conditions, including different weather scenarios and angles of visibility. The AI system's ability to recognize small objects is improved by incorporating advanced object detection techniques. The company also addresses the workers' concerns about privacy by ensuring that the AI is only used to monitor safety compliance and that personal data is protected.

8.2.4 Outcomes

With these adjustments, the AI system successfully identifies hazards in real-time with high precision, reducing the number of accidents on-site. The safety compliance rate improves, and the AI system generates timely alerts that allow safety officers to intervene before incidents occur. Overall, the implementation of AI not only enhances the company's safety protocols but also leads to a more efficient workflow by automating many aspects of safety monitoring.

8.3 Third Case Study: AI application at Neom

(Hassan, 2020) used Saudi Arabia's ambitious Neom project as a case study to explore the integration of AI into **economic diversification efforts**. Neom, a futuristic city being built in the northwestern region of Saudi Arabia, aims to be a hub for technological innovation, with AI at the core of its operations. The project is designed to reduce Saudi Arabia's reliance on oil revenues, with AI technologies playing a key role in achieving this diversification by driving efficiency and innovation across multiple sectors, including construction, energy, and transportation.

8.3.1 AI Implementation

At the heart of Neom's construction process is the integration of **AI and advanced robotics** to manage various aspects of project planning and execution. AI systems are used to optimize resource allocation, monitor construction sites in real time, and ensure that sustainability targets are met. The AI models analyze vast amounts of data from drones and IoT devices installed across the construction site to predict potential project delays, optimize logistics, and reduce energy consumption. In addition, the use of **AI-driven simulations** allows planners to test different urban layouts and infrastructure designs before any physical work begins.

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8.3.2 Challenges Faced

One of the initial challenges in integrating AI into Neom's construction process was the complexity of managing and processing the massive amounts of data generated by the city's vast network of sensors and connected devices. The AI system had to be fine-tuned to handle both the volume and variety of data streams, ranging from weather patterns to real-time traffic updates. Another challenge was ensuring that the AI systems were aligned with the ambitious sustainability goals of the project, as AI-driven construction tools required significant energy to function, sometimes contradicting the city's green objectives.

8.3.3 How Challenges Were Addressed

To overcome these challenges, Neom's planners partnered with leading AI companies and research institutions to develop specialized AI models capable of handling complex urban data. The project also invested in renewable energy sources, such as solar and wind power, to offset the energy demands of its AI systems. Additionally, a modular approach to AI implementation was adopted, allowing the systems to be gradually integrated and tested across different aspects of the project, ensuring flexibility and minimizing disruptions to the overall timeline.

8.3.4 Outcomes

As a result of AI integration, Neom achieved **significant improvements in construction efficiency**. AI systems reduced project delays by 30% through better resource management and automated scheduling, while real-time monitoring enhanced safety across the construction sites. Furthermore, AI-driven sustainability tools helped reduce the overall carbon footprint of the project by optimizing energy usage and waste management processes. The successful implementation of AI in Neom not only demonstrated its potential to transform construction projects but also underscored Saudi Arabia's commitment to becoming a global leader in technological innovation as part of its Vision 2030 plan.

8.4 Fourth Case Study: Visual Pollution Management

In this study conducted by (Algallf, et al, 2024) a Saudi municipality undertakes an initiative in cooperation with SAADIA to utilize AI technology for monitoring and reducing **visual pollution** across its urban areas. Inspired by the systems described in the study, the municipality integrates **machine learning** and **big data analytics** into its urban management strategies to detect and mitigate the effects of visual pollution, which includes illegal advertising, graffiti, and poorly maintained signage.

8.4.1 AI Implementation

The AI system, using a combination of **deep learning** and **computer vision**, analyzes images captured from dash cams and citizen-reported cases through mobile applications such as "Baladi Lens." The system automatically detects instances of visual pollution and classifies them based on severity, enabling authorities to prioritize and address the most pressing cases first. It also tracks trends in visual pollution, allowing the municipality to allocate resources more effectively by focusing on areas with higher incident rates.

8.4.2 Challenges Faced

One of the primary challenges in implementing the AI system was ensuring its accuracy in identifying visual pollution in different environmental conditions, such as low light or in areas with high levels of visual clutter. Another challenge involved integrating AI with the municipality's existing data management platforms, which required adjustments to handle the large influx of real-time data generated by dash cams and citizen reports. There were also concerns among some municipal workers regarding the potential impact of AI on their roles and responsibilities, as some feared job displacement due to automation.

8.4.3 How Challenges Were Addressed

To improve the accuracy of pollution detection, the AI model was trained on a diverse set of images representing various lighting conditions and environmental factors. Additionally, the municipality upgraded its data infrastructure to handle the increased data flow, ensuring that the AI system could process information in real time. To address concerns about job displacement, the municipality introduced AI training programs to help workers transition into more supervisory and analytical roles, where they could oversee AI operations and focus on tasks that require human judgment.

8.4.4 Outcomes

The AI-driven system significantly increased the municipality's efficiency in handling visual pollution. Detection accuracy improved by 25%, while response times to citizen reports decreased by 30%. The initiative led to a 40% reduction in overall cases of visual pollution, as the municipality could now identify and address issues more proactively. Additionally, the AI system provided valuable data insights, helping the municipality predict future trends and allocate resources more effectively, further enhancing the city's efforts to maintain a cleaner, more visually appealing environment.

8.5 Fifth Case Study: AI Adoption in King Salman Energy Park "SPARK"

The King Salman Energy Park in Saudi Arabia is another example of the integration of AI technologies in the construction industry. This mega-project, which aims to become a global energy hub, has incorporated AI-powered systems to optimize various aspects of

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construction and operations. For instance, the project utilizes AI-driven building information modeling to streamline the design and planning process, enabling more efficient collaboration among project stakeholders. Additionally, the use of AI-powered autonomous vehicles and robotics on the construction site has improved site safety and productivity. It offers infrastructure that can support the adoption of advanced AI technologies in the construction industry, which highlights the growing momentum towards embracing AI-driven solutions in the Saudi construction sector.

9. SURVEY FINDINGS AND DISCUSSION

In this study, we conducted a comprehensive survey to gather insights into the adoption of artificial intelligence (AI) in the construction industry in Saudi Arabia. The survey, which received 60 responses from professionals across various sectors within the industry, aimed to identify key challenges and potential solutions related to AI implementation. The questions covered a broad spectrum of aspects, including technical, regulatory, economic, and social challenges, as well as the perceived benefits and practical applications of AI. The findings offer valuable perspectives that both confirm and challenge the assumptions made in our study, providing a foundation for targeted strategies to enhance AI adoption in the construction sector.

9.1 Technical Challenges

The survey findings confirm that technical challenges are among the primary obstacles to AI adoption in the Saudi construction industry. Respondents frequently highlighted integration difficulties, particularly in ensuring compatibility between AI systems and existing tools such as Building Information Modeling (BIM). Additionally, data quality emerged as a critical issue, as incomplete or unreliable data can hinder AI's effectiveness in delivering accurate insights. These findings strongly align with the assumptions made, emphasizing that seamless AI integration and data management enhancements are essential. Addressing these challenges requires developing robust, adaptable AI solutions capable of working with legacy systems while improving data accuracy and accessibility.

9.2 Regulatory and Legal Challenges

Regulatory and legal issues pose significant barriers to AI adoption in the construction industry, as confirmed by the survey responses. Many participants pointed to unclear regulations and insufficient compliance standards as key challenges that slow down AI integration. Data privacy and ethical considerations also featured prominently among respondents' concerns. This aligns well with the assumptions made in the paper regarding the need for comprehensive regulatory frameworks and transparent legal protocols. To foster broader adoption of AI, it is crucial to establish clear guidelines that address these regulatory challenges while safeguarding data security and ethical use.

9.3 Economic Challenges

Economic constraints were consistently highlighted by survey participants as major obstacles to AI adoption. Respondents cited high implementation costs, difficulties in demonstrating return on investment (ROI), and a shortage of skilled talent as significant barriers. These findings validate the assumptions that economic factors, including cost concerns and limited access to expertise, are hindering the adoption of AI in construction projects. To overcome these barriers, strategies such as financial incentives, cost-effective AI solutions, and investment in AI-related education and training programs are necessary to make AI adoption more accessible and beneficial for the construction industry.

9.4 Social Challenges

Social factors also play a critical role in limiting AI adoption, as indicated by the survey findings. Resistance to change, particularly among project managers and construction workers, was a common theme, driven by concerns about job displacement and unfamiliarity with AI technologies. The survey responses mirror the assumption that social challenges, including workforce adaptation and cultural resistance, pose significant barriers. To address these issues, it is essential to invest in awareness campaigns that communicate the benefits of AI, offer training programs to upskill the workforce, and implement change management strategies that foster a positive outlook on AI-driven innovation.

10. CONCLUSION

This study has explored the integration of Artificial Intelligence (AI) within the Saudi construction industry, outlining key assumptions about its challenges and opportunities. The assumptions included technical barriers, such as data quality and integration issues, regulatory challenges related to unclear guidelines and compliance, economic concerns surrounding high costs and limited ROI, and social obstacles like resistance to change and workforce adaptation. Hypothetical scenarios and survey findings highlighted how these challenges manifest in practice and illustrated potential solutions.

The potential of AI to revolutionize the Saudi construction industry is immense. AI-driven technologies can optimize resource allocation, improve project planning and execution, enhance safety through real-time monitoring, and ultimately reduce costs and delays. These benefits align with Saudi Arabia's Vision 2030 goals of economic diversification and technological innovation.

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However, realizing this potential requires overcoming significant barriers through tailored regulatory frameworks, cost-effective solutions, robust data management practices, and proactive change management strategies to foster workforce acceptance and readiness.

While this paper has presented hypothetical findings based on assumptions and survey insights, further research is necessary to validate these assumptions and explore practical AI implementation strategies. Collaboration between industry stakeholders, policymakers, and technology providers will be essential to unlocking AI's full capabilities and ensuring its effective integration into Saudi Arabia's construction sector. By addressing these challenges, industry can pave the way for a smarter, more efficient, and innovative-driven future.

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الاستفادة من الذكاء الاصطناعي للابتكار في إدارة المشاريع استكشاف الإمكانيات

والتطبيقات" دراسة حالة إدارة التشوه البصري في أمانة مدينة جدة"

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الاصطناعي للابتكار في إدارة المشاريع استكشاف الإمكانيات والتطبيقات" دراسة حالة إدارة التشوه البصري في

أمانة مدينة جدة"، **المجلة العلمية للتجارة والتمويل**، المجلد ٤٤ (3) .

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للتواصل مع المؤلف:¹

الاستفادة من الذكاء الاصطناعي للابتكار في إدارة المشاريع استكشاف الإمكانيات والتطبيقات" دراسة حالة إدارة التشوه البصري في أمانة مدينة جدة"

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تاريخ المادة

تم استلامه في 9 يوليو 2024 ، وتم قبوله في 8 أغسطس 2024، وهو متاح على الإنترنت سبتمبر 2024

ملخص البحث:

تهدف هذه الورقة البحثية إلى استكشاف إمكانيات استخدام تقنيات الذكاء الاصطناعي لإحداث ثورة في إدارة المشاريع، مع التركيز على تطبيقها في رصد ومعالجة التشوه البصري في مدينة جدة. من خلال استكشاف كيفية مساهمة الذكاء الاصطناعي في تطوير المدن الذكية، تسلط هذه الدراسة الضوء على جهود أمانة مدينة جدة لتحسين البنية التحتية، وتعزيز الخدمات، وتعزيز مكانتها كمدينة مستدامة وذكية تستجيب بفعالية لاحتياجات سكانها وتحديات المستقبل. تستعرض الورقة مصادر التشوه البصري في مدينة جدة وتقيم طرق رصدها ومعالجتها. تقدم الدراسة رؤى مفصلة حول التحديات والفرص المرتبطة باستخدام الذكاء الاصطناعي لإدارة التشوه البصري. تكشف الدراسة عن كيفية التعامل مع بيانات التشوه البصري عادةً من خلال الإدخال اليدوي والتحليل باستخدام أدوات مثل برنامج إكسل، وسجلات البيانات Data Records وتعلم الآلة Machine Learning وتحليل البيانات الضخمة Big data analysis.

تم استخدام منصات وتطبيقات حكومية رئيسية، مثل منصة "ممثل" لإدارة الرقابة البلدية وتطبيق "بلدي لنس" الذي يستخدم الهواتف المحمولة ككاميرات داش كام، لتمكين دمج الذكاء الاصطناعي في إدارة المدن. ساعدت هذه الأدوات البلديات في تحديد ومعالجة التشوهات البصرية، مما أدى إلى تحسين المشهد الحضري. على سبيل المثال،

ساهم استخدام تطبيق "بلدي لنس" في زيادة دقة رصد التشوه البصري بنسبة 25% وتقليل وقت الاستجابة للشكاوى بنسبة 30%.

على الرغم من التحديات مثل دقة رصد الانتهاكات، وعمليات التحقق، والأتمتة الكاملة، والقيود الزمنية، فقد أثبتت التطبيقات الحالية للذكاء الاصطناعي فعاليتها. على سبيل المثال، تم تحقيق تقليل بنسبة 40% في حالات التشوه البصري خلال فترة الدراسة، وارتفعت معدلات الرصد وتغطية المناطق المستهدفة بنسبة 93%، وهذا يبرز الحاجة إلى دمج حلول الذكاء الاصطناعي في تخطيط المدن الذكية وإدارة التشوه البصري لتحقيق التنمية الحضرية المستدامة. تقدم هذه الدراسة رؤى قيمة للباحثين وصناع القرار في البلديات والجهات ذات العلاقة الذين يسعون لتحسين جودة المشهد الحضري والتصميم في المدن الذكية، مع استخدام مدينة جدة كدراسة حالة.

Abstract:

This research paper investigates the potential of artificial intelligence (AI) technologies to revolutionize project management, with a focus on their application in monitoring and addressing visual pollution in Jeddah City. By exploring how AI can contribute to the development of smart cities, this study highlights Jeddah City's Municipality efforts to improve infrastructure, enhance services, and bolster its status as a sustainable and responsive smart city. The paper reviews sources of visual pollution in Jeddah and evaluates methods for detection, monitoring, and solving.

The study presents detailed insights into the challenges and opportunities associated with leveraging AI for visual pollution management. It reveals how visual pollution data is typically handled through manual input and analysis using tools like Microsoft Excel, alongside advanced Machine Learning and Big Data Analytics techniques to uncover hidden patterns within historical data trends.

Key government platforms and applications, such as the "Mumathil" platform for municipal oversight and the "Baladi Lens" application, which uses mobile devices as dashcams, have been employed to enable AI integration in urban management. The use of the "Baladi Lens" application for instance, has increased the accuracy of visual pollution detection by 25% and reduced response time to complaints by 30%.

Despite challenges such as accuracy in monitoring violations, verification processes, full automation, and time constraints, the currently implemented AI applications have proven effective. A 40% reduction in visual pollution cases and a 93% increase in detection rates and coverage of targeted areas were achieved during the study period. This underscores the need to integrate AI solutions into smart city planning and visual pollution management for sustainable urban development. This research offers valuable insights for researchers and decision-makers in municipalities and related authorities aiming to improve visual quality and urban design for smart cities, using Jeddah as a case study.

الكلمات المفتاحية:

الذكاء الصناعي، تعلم الآلة (Machine Learning); تحليل البيانات الضخمة (Big data analysis);

إدارة التشوه البصري; المدن الذكية; التنمية الحضرية; أمانة مدينة جدة

1. المقدمة:

في العقود الأخيرة، شهد العالم تطورات مذهلة وجديدة في مجال الذكاء الاصطناعي لتحسين الحياة اليومية وتعزيز كفاءة العمليات في مختلف القطاعات. الذكاء الاصطناعي، بتقنياته المتقدمة وقدراته الفريدة، بات يمثل حجر الزاوية في مسيرة تطوير المدن الذكية، حيث يساهم في تحسين البنية التحتية، إدارة الموارد والمرافق بكفاءة، تعزيز الأمن العام، وتحسين جودة الخدمات المقدمة للسكان. هذه التحولات تعد ضرورية لمواجهة التحديات العمرانية والبيئية والاجتماعية التي تواجهها المدن المتنامية بشكل متسارع.

أدى ظهور الذكاء الاصطناعي والتقنيات ذات الصلة منذ عام 2019 إلى تقديم حلول مبتكرة في مجالات الاستدامة البيئية، والتغير المناخي، وتطوير المدن الذكية. وقد مكّن الذكاء الاصطناعي من تحليل البيانات الضخمة الناتجة عن أجهزة إنترنت الأشياء في المدن الذكية، مثل أجهزة الاستشعار والكاميرات، التي تجمع بيانات مستمرة عن جودة الهواء، حركة المرور، واستهلاك الطاقة. بالإضافة إلى ذلك، تُستخدم هذه الأجهزة للكشف عن التشوهات البصري من خلال جمع صور وفيديوهات لمظاهر التشوه البصري في المدينة. هذه البيانات تعزز عملية صنع القرار من خلال توفير معلومات دقيقة في الوقت الفعلي، وتتيح تفاعلاً فعالاً بين البشر والآلات في أنظمة الحوسبة والذكاء المتطورة، مما يساهم في تحسين إدارة التشوه البصري وتحقيق التنمية الحضرية المستدامة. (Bibri et al., 2023)

يلعب الذكاء الاصطناعي دوراً حاسماً في تعزيز النمو البيئي من خلال تمكين المباني الذكية وأنظمة النقل الذكية وإدارة المدينة الفعالة، وبالتالي تعزيز الفعالية وتبسيط استخدام الموارد. إن دمج الذكاء الاصطناعي في أطر المدن الذكية يعزز التنمية الاقتصادية ويعزز مستويات المعيشة ويسهل الإشراف المستدام على الأصول الطبيعية من خلال التوافق بين أنظمة الرصد ورؤية النمو البيئي.

حديثاً تم إطلاق مبادرة جودة الحياة كجزء من رؤية المملكة 2030، ويتم توظيف تكنولوجيا الذكاء الاصطناعي لتحسين مستويات معيشة السكان من خلال زيادة المشاركة في الفعاليات الاجتماعية والثقافية. هذه المبادرة تسعى جاهدة لوضع المدن السعودية بين أكثر المدن الصالحة للسكن على مستوى العالم، مع التركيز على جميع السكان داخل المملكة العربية السعودية. مدينة جدة، باعتبارها واحدة من أبرز المدن في المملكة العربية السعودية وبوابة الحرمين الشريفين، تقف على أعتاب فرصة ذهبية للتحويل إلى مدينة ذكية رائدة من خلال استغلال الذكاء الاصطناعي. هذا البحث يستهدف استكشاف كيف يمكن لتقنيات الذكاء الاصطناعي أن تساهم في تطوير مدينة جدة، ليس فقط لتحسين البنية التحتية والخدمات، ولكن أيضاً لتعزيز مكانتها كمدينة مستدامة وذكية تستجيب لاحتياجات سكانها ومواجهة التحديات المستقبلية بفعالية.

من خلال تحليل متعمق للفرص التي يقدمها الذكاء الاصطناعي والتحديات التي قد تواجه تطبيقه في سياق مدينة جدة، يهدف هذا البحث إلى تقديم رؤى قيمة وتوصيات عملية تساعد في رسم مسار التطوير الذكي للمدينة. سيتم

ذلك من خلال استعراض تطبيقات الذكاء الاصطناعي في مجالات مختلفة مثل إدارة المرور والنقل، الإدارة الذكية للموارد، الرعاية الصحية، والأمن العام، مع التركيز على دراسات حالة مبادرات ناجحة من مدن أخرى حول العالم. بالنظر إلى الطموح الكبير للمملكة العربية السعودية في رؤية 2030 والدور الهام الذي تلعبه مدينة جدة في هذا السياق، يمثل هذا البحث خطوة مهمة نحو فهم وتحقيق إمكانات الذكاء الاصطناعي في تحقيق تطور شامل ومستدام للمدينة، بما يتماشى مع الأهداف الاستراتيجية للمملكة وتطلعات سكان مدينة جدة وسوف يتطرق هذا البحث للمخالفات البيئية الموجودة على أرض الواقع في مدينة جدة وعلى رأسها التشوه البصري.

أما بالنسبة لتعريف التشوه البصري، فإنها تختلف باختلاف شموليتها للمخالفات البيئية لذلك نستعرض هنا بعض التعريفات للتلوث البصري حتى يتضح المعنى بشكل أفضل. التشوه البصري الذي يعرف على أنه ضعف الجودة البصرية للمنطقة من خلال الإعلانات واللافتات غير الضرورية ، يشمل الآن أي عنصر يسبب فوضى قائمة على المناظر الطبيعية. يمكن أن يؤدي التعرض للتلوث البصري إلى عواقب عقلية وجسدية سلبية (AlElaiwi et al., 2023).

أما أحمد، فإنه يوصف التشوه البصري بأنه مصدر قلق جديد نسبياً ضمن الطيف الأوسع للتلوث البيئي ، مما يستلزم البحث لتصوره وإضفاء الطابع الرسمي عليه وتحديد وتقييمه من أبعاد مختلفة. وهو يشمل غير المرغوب فيه وغير الممتع. (Ahmed et al., 2019).

تتناول الدراسة الصعوبات التي تواجهها تطبيقات الذكاء الاصطناعي في تحديد وتصنيف الملوثات البصرية، والتي تنشأ من اختلافاتها غير المحدودة في الشكل واللون والأبعاد، مما يجعلها أحد التحديات التي تتطلب مجموعات بيانات واسعة للتدريب. تقدم هذه التطبيقات نهجاً واعدًا لأتمتة عملية التصنيف، ومع ذلك، يبقى التحدي في تطوير نظام قادر على محاكاة الإدراك البشري عن كثب في تحديد الملوثات البصرية. بالإضافة إلى ذلك، تواجه إدارة عمليات الرصد تحديات في تحديد المتسببين في التشوه البصري بدقة، حيث يتطلب ذلك دمج البيانات من مصادر متعددة مثل سجلات العقارات والكاميرات المراقبة، لتحليل الأنماط وتحديد المسؤولين عن المخالفات. استخدام الذكاء الاصطناعي يساهم في تحسين هذه العمليات من خلال تحليل البيانات الكبيرة وتوفير نتائج دقيقة وسريعة، مما يساعد في اتخاذ قرارات مبنية على الأدلة وتقليل التشوه البصري بفعالية.

2. مشكلة الدراسة:

تعد مشكلة التشوه البصري مصدر قلق جديد نسبياً ضمن الطيف الأوسع للتلوث البيئي، مما يستلزم البحث لتصوره وإضفاء الطابع الرسمي عليه وتحديد وتقييمه من أبعاد مختلفة. تكمن المشكلة في المناظر غير المرغوب فيها والتي تندرج تحت عنوان التشوه البصري. تأتي أهمية معالجة التشوه البصري كجزء لا يتجزأ من رؤية المملكة 2030 وبرنامج جودة الحياة، حيث تسعى هذه المبادرات إلى تحسين جودة الحياة وتعزيز البيئة الحضرية للسكان.

تحقيق أهداف رؤية 2030 يتطلب الاهتمام بالتفاصيل الجمالية للمدن، والعمل على إزالة مظاهر التشوه البصري لتحسين المشهد الحضري، ودعم التنمية المستدامة.

3. هدف الدراسة:

دراسة حالة: استكشاف إمكانيات الذكاء الاصطناعي في إدارة التشوه البصري في أمانة مدينة جدة. تهدف دراسة الحالة الى بحث امكانية ودور الذكاء الاصطناعي في إحداث ثورة في إدارة المشاريع عامةً و في إدارة مكافحة التشوه البصري بأمانة مدينة جدة بصورة خاصة، مع التركيز على كيفية تجاوز التحديات التي تطرحها الأساليب التقليدية لإدارة عمليات الرصد مثل الحاجة إلى تحسين الوقت، الكفاءة، الدقة، وتوزيع الموارد. بفضل قدرة تطبيقات الذكاء الاصطناعي على سرعة الرصد وعلى تحليل البيانات الضخمة وتقديم حلول دقيقة بسرعة فائقة، حيث يعد الذكاء الاصطناعي أداة محورية لتعزيز أداء وفعالية إدارة هذه المشاريع من خلال تقديم نماذج تحليلية متقدمة. ويمكن للذكاء الاصطناعي تحديد نقاط الضعف في الاستراتيجيات الحالية واقتراح تحسينات تستهدف استغلال الموارد بشكل أمثل وتقليل الوقت اللازم لتنفيذ المشاريع. في هذا القسم سيتم استعراض الطرق التقليدية التي تم استخدامها والتحديات الناتجة عنها والطرق الحديثة لعمليات رصد ومتابعة التشوه البصري في مدينة جدة.

4. أهمية الدراسة

تكتسب هذه الدراسة أهمية كبيرة نظرًا لتأثير التشوه البصري السلبي على جودة الحياة والبيئة الحضرية في مدينة جدة. التشوه البصري لا يقتصر فقط على التأثير البصري، بل يمتد ليشمل جوانب نفسية وصحية للسكان، مما يجعل من الضروري البحث عن حلول فعالة ومستدامة لمعالجته. تسعى هذه الدراسة إلى تحسين البيئة الحضرية ودعم رؤية 2030 من خلال تطبيق تقنيات الذكاء الاصطناعي لتحسين جودة الحياة وتحقيق التنمية المستدامة عن طريق ادارة عمليات رصد ومعالجة التشوه البصري.

تعد هذه الدراسة رائدة في استكشاف إمكانيات الذكاء الاصطناعي في تحويل مدينة جدة إلى مدينة ذكية. من خلال استخدام الذكاء الاصطناعي، يمكن تعزيز كفاءة عمليات رصد وإدارة التشوه البصري، مما يساهم في تسريع اتخاذ القرارات وتحسين الاستجابة للمخالفات البيئية. ستوفر هذه الدراسة نماذج وحلول مبتكرة يمكن تطبيقها في سياقات مشابهة، مما يساهم في تطوير ممارسات الإدارة الحضرية وتقليل التكاليف وزيادة الفعالية.

كما تساهم هذه الدراسة أيضًا في توسيع الفهم النظري والتطبيقي لاستخدام الذكاء الاصطناعي في إدارة المدن الذكية، مما يعزز البحث العلمي في هذا المجال. كما تقدم نتائج الدراسة رؤى قيمة لصناع القرار والمخططين الحضريين، حيث يمكنهم استخدامها لتطوير استراتيجيات وسياسات أكثر فعالية في إدارة التشوه البصري وتحسين المشهد الحضري. من خلال تقديم حلول مبتكرة ومستدامة، تسعى هذه الدراسة إلى دعم التنمية الحضرية المستدامة وتعزيز جودة الحياة في مدينة جدة.

5. الدراسات السابقة:

5.1. دراسة مايانك ميشرا و باولو لورنسو (2024)

تناولت الدراسة استخدام تقنية الذكاء الاصطناعي في المساعدة في تفتيش التراث الثقافي عبر تقديم نظرة شاملة على تقنيات الذكاء الاصطناعي والشبكات العصبية في رصد وحماية المواقع التراثية. وركزت الدراسة على كيفية استخدام هذه التقنيات في الكشف عن العيوب والتلفيات الهيكلية في المباني التراثية مما يساعد على تحديد أماكن التلفيات وأنواعها بدقة. وتطرقت الدراسة أيضاً إلى دور التقنية في تحسين جهود الحفاظ على التراث والثقافة وتسهيل عمليات التفتيش والصيانة. كما تطرقت الدراسة إلى المزايا والقيود المتعلقة بهذه التقنيات و سلطت الضوء على أهمية الاستمرار في البحث والتطوير في هذا المجال لتعزيز جهود الحفاظ على التراث الثقافي.

5.2. دراسة سيندو ريدي ناجيريدي (أغسطس ٢٠٢٣)

ركزت الدراسة على استخدام الذكاء الاصطناعي في مجال إدارة المشاريع بهدف تغيير طرق تنفيذ مهام مديري المشاريع باستخدام خوارزميات الذكاء الاصطناعي المستخدمة في إدارة المشاريع. وقد قام الباحث باستخدام المنهج النوعي وكانت عينة البحث من العاملين في مجال إدارة المشاريع ممن لا تقل خبرتهم العملية عن ٣ سنوات. وبناء على ما تم الحصول عليه من معلومات توصل الباحث إلى وجود حاجة إلى استخدام تقنية الذكاء الاصطناعي في إدارة المشاريع لتعزيز إنتاجية مديري المشاريع واستخدامه في التخطيط للمشاريع وإدارة الموارد واتخاذ القرارات.

5.3. دراسة زهراء هادي كاظم (أبريل 2023)

تناولت الدراسة أثر التشوه البصري في محافظة بابل على الذائقة الجمالية للعرض الحضري حيث ركزت الدراسة على انتشار الفوضى في مركز المحافظة مثل الهياكل غير المتناسقة ونقص عناصر التصميم المعاصرة والشوارع الضيقة المتهاكة وغياب الساحات العامة الترفيهية والمساحات الخضراء وغياب المعايير الجمالية الحضرية في المنطقة. وقد قامت الباحثة برصد 50 مشهداً كمجتمع للبحث تمثل موضوع البحث عن طريق الجولة الميدانية والتقاط الصور وكانت عينة البحث مكونة من 5 مشاهد تم اختيارها بالطريقة القصدية وتم استخدام المنهج الوصفي التحليلي. وقد أشارت نتائج البحث إلى أن للتشوه البصري دوراً كبيراً في التأثير على الذائقة الجمالية للعرض الحضري في محافظة بابل وأكدت على وجود فوضى و تشوهات بصرية في المنطقة. تلخصت أهم التوصيات في تحسين التخطيط والتنظيم الحضري لتحسين الجودة البصرية والجمالية للمنطقة واستخدام التصاميم المعاصرة وتوفير الساحات العامة الترفيهية والمساحات الخضراء كما أوصت بتفعيل التواصل بين المجتمع المحلي والمسؤولين من أجل تحسين العرض الحضري والتوعية بأهمية الجمالية الحضرية والحث على المشاركة المجتمعية في تطوير المنطقة وتحسين الذوق الجمالي.

5.4. دراسة محمد بيرات حسين وآخرون (2023)

قام الباحثون بإجراء دراسة بغرض تحليل وكشف التشوه البصري باستخدام نظام مبني بتقنية الذكاء الاصطناعي للكشف عن التشوه البصري بشكل تلقائي بحيث تكون عملية جمع البيانات وتحليلها مستمرة بغرض تحسين النظام وتم استخدام مفاهيم التعلم النشط والتعلم التدريجي بهدف تحسين أداء النماذج المدربة. تم استخدام نموذج YOLOv5 ونموذج Faster R-CNN ونموذج EfficientDet وقد أظهر النموذج الأول تفوقه على النموذجين الآخرين وقد استخدم الباحثون نظام أندرويد لتسهيل عملية تقديم الصور التي تحتوي على تلوث بصري مع إحداثيات الموقع مما يساعد الجهات ذات الصلة لرصد التشوه البصري وتحديد الموقع الجغرافي.

5.5. دراسة يوجيشواري شوارج و روبيش كين سونجكور (مايو ٢٠٢٢)

هدفت الدراسة إلى إدارة الوقت في المشاريع وتحديدًا مشاريع البرمجيات حيث قام الباحثان بإجراء مقابلات مع الموظفين وتعرفوا على المشكلة التي تواجه الموظفين وهي تلبية المتطلبات بحسب المواعيد في المشاريع. وقد أوصت الدراسة بأن يتم إدخال نظام الذكاء الاصطناعي وأدواته في مجال العمل وتدريب الموظفين على استخدامه من أجل تحسين عملية إدارة المشاريع.

5.6. دراسة ريم محمد باوارث (فبراير 2022)

قامت الباحثة في دراستها على التعرف على التشوه البصري ومظاهره وأسباب ظهوره وأثره على صحة الإنسان حيث تم تطبيق الدراسة في بعض أحياء مدينة جدة. وقد تم استخدام المنهج الوصفي التحليلي في دراسة مظاهر التشوه البصري على عينة الدراسة وتم رصد مختلف أنواع التشوه البصري مثل النمط العمراني والملصقات الإعلانية والكتابة على الجدران. وخلصت الدراسة إلى وجود تباين في التشوه البصري بين الأحياء محل الدراسة وأوصت الدراسة إلى الحاجة لزيادة الوعي البصري وتحسين المشهد الحضري للأحياء.

5.7. دراسة سويتا بهاتشاريا وآخرون (2022)

قام الباحثون بدراسة استخدام تقنية التعلم العميق في تحليل البيانات في المدن الذكية بغرض تحسين إدارة الموارد ومن ثم تم التركيز على تطبيقات مختلفة وتجربتها على إدارة المرافق في المدن الذكية كنظام الإضاءة وسرعة ربط شبكات المرور. وقد خلصت الدراسة إلى أن استخدام عملية التعلم العميق يساهم في تطوير العديد من الأنظمة الآلية التي تساعد على تحسين جودة الحياة من الناحية الطبية ومن ناحية إدارة المدن الذكية أيضاً مما يساهم في توفير بيئة آمنة وصحية للمواطنين. وقد أوصت الدراسة إلى زيادة الاستثمار في بنية الإنترنت والتكنولوجيا التي تساعد على جمع البيانات وتعزيز البحث والتطوير في مجال البيئة الذكية والتعاون مابين القطاع العام والخاص لتبادل الخبرات والمعارف.

5.8. دراسة عثمان يوما وآخرون (2021)

قام الباحثون باستخدام تقنيات التعلم العميق و الاستشعار عن بعد للكشف عن عمليات تفريغ النفايات باستخدام طائرات بدون طيار في منطقة سانت لويس في السنغال حيث تم استخدام شبكات العصب العميقة في تحليل الصور المأخوذة من الطائرات وأظهرت النتائج أن النموذج يتعرف على المناطق المعنية بشكل جيد مع وجود صعوبات في بعض المناطق التي تقتصر إلى حقائق أساسية. كما بينت النتائج أن استخدام هذه التقنيات في عملية الكشف عن أماكن النفايات يعد أسلوباً ممتازاً وذلك للدقة العالية في تحديد مكان وأنواع النفايات. وقد أوصت الدراسة بإعادة بناء نموذج لكشف المناطق غير المغطاة ونموذج آخر للمناطق المغطاة.

5.9. دراسة خديجة واكلي وآخرون (2019)

تناولت الدراسة التحديات في عملية تقييم ورسم خرائط التشوه البصري في المدن وناقشت رصده باستخدام التطبيقات مفتوحة المصدر لرسم خرائط التشوه البصري. كما بحثت الدراسة إمكانية قياس التشوه البصري بفعالية في المدن في وقت وتكلفة أقل بواسطة التطبيقات مفتوحة المصدر مثل OpenGeo Suite و PostgreSQL و Open Data Kit (ODK) بحيث يتم تطوير نظام لجمع بيانات التشوه البصري في المدن باستخدام الأجهزة المحمولة وجمع البيانات وإدارتها عبر خادم على الإنترنت ومن ثم تحليل التشوه البصري المرصود. وقد توصلت الدراسة إلى إمكانية الاستفادة من التطبيقات مفتوحة المصدر في قياس التشوه البصري بفعالية كما شددت على أهمية توفير الدعم للموارد البشرية التي ستقوم بعملية الرصد باستخدام الأجهزة المحمولة. وأوصت الدراسة بتوفير تدريب مكثف للمختصين وبالأخص القوائم على تخطيط المدن لاستخدام أدوات تقييم التشوه البصري.

5.10. دراسة خديجة واكلي وآخرون (2019)

تستعرض الدراسة ضرورة تقييم التشوه البصري في البيئات الحضرية وأهمية وجود أداة لتقييم هذا التلوث حيث يقدم الباحث هذه الأداة لتسهيل عملية تقييم التشوه البصري. ويتمثل التحدي بحسب رأي الباحثين في تحديد وتصنيف العناصر المسببة للتلوث البصري وتقييم تأثيرها على البيئة والصحة العامة. وقد تم اقتراح وتطوير أداة تستخدم تقنية تحليل الهرم التسلسلي والمسح العام والمسابقة الفوتوغرافية لتحديد العناصر المسببة للتلوث البصري وتصنيفها. وكان من نتائج الدراسة أن الإدارة المقترحة توفر تقييم للتلوث البصري عبر قياس وجود خصائص مختلف العناصر المسببة للتلوث البصري كما تبين أيضاً مستوى التشوه البصري على مقياس من 1 إلى 100 وبين أيضاً أن هذه الأداة تعتمد على آراء الخبراء مما يجعلها قوية ومناسبة لمعظم المناطق الحضرية في الدول النامية ويمكن أن تساعد أصحاب القرار الحكومي ومخططي المدن في فهم أفضل لانتشار التشوه البصري.

6. منهجية الدراسة (دراسة الحالة):

تهدف الدراسة إلى بحث واستكشاف الكيفية التي يمكن للذكاء الاصطناعي (AI) أن يقود الابتكار في إدارة المشاريع، وبالتحديد معالجة التشوه البصري في أمانة مدينة جدة باستخدام سجلات البيانات Data Records وتعلم الآلة

Machine Learning وتحليلات البيانات Data analytics، والتعامل مع البيانات الضخمة Big Data، والكشف عن أنماط مخفية ضمن اتجاهات التشوه البصري التاريخية. سيساعدنا هذا النهج المدعوم بالذكاء الاصطناعي على فهم تحديات أمانة مدينة جدة في إدارة التشوه البصري والمعوقات التي واجهتها باستخدام طرق الرصد التقليدية، ومن ثم تطوير استراتيجيات أفضل لمعالجة ومواجهة تحديات رصد ومعالجة التشوه البصري.

سيتم استخدام دراسة الحالة للتعلم في تعقيدات إدارة التشوه البصري بالطرق التقليدية، وبحث ما إذا كانت تطبيقات الذكاء الاصطناعي تساهم في تحديد أوجه عدم الكفاءة، وتقييم استخدام الذكاء الاصطناعي الحالي، والتنبؤ بنقاط التلوث، واقتراح حلول مصممة خصيصًا للسياق الحضري في مدينة جدة. سيظهر تحليلنا للبيانات التاريخية والبيانات في الوقت الفعلي كيف يمكن للذكاء الاصطناعي تحسين إدارة المشاريع التقليدية من خلال تعزيز عملية صنع القرار وتقليل الأخطاء، وتخفيف المخاطر، والتعامل مع مجموعات البيانات المعقدة بكفاءة وتوزيع الموارد. كما يمكن أن يساهم في مدى تكامل هذه التطبيقات مع الجهات الأخرى ذات العلاقة. يقدم هذا البحث في النهاية رؤية قيمة للباحثين وصناع القرار في الأمانات والجهات ذات العلاقة الذين يسعون إلى تحسين الجودة البيئية والتصميم الحضري في جدة وخارجها.

توفر أمانة مدينة جدة دراسة حالة مثالية لاستكشاف دور الذكاء الاصطناعي في معالجة التشوه البصري في الأماكن الحضرية المعقدة. يخلق مزيجها الفريد من التطور التاريخي والحديث، إلى جانب موقعها كبوابة للحرمين الشريفين، تحديات محددة للتلوث البصري مثالية لاختبار قدرة الذكاء الاصطناعي على رصد ومعالجة التشوه الحضري وتحسين جماليات المناطق الحضرية. بالإضافة إلى ذلك، فإن الموقف الاستباقي للأمانة تجاه الحلول التكنولوجية في الإدارة الحضرية يوفر بيئة داعمة وبيانات غنية للأبحاث التي تركز على الذكاء الاصطناعي. من خلال التركيز على جدة، يمكننا إظهار كيف يؤدي تحليل الذكاء الاصطناعي لبيانات التشوه البصري إلى رؤية قابلة للتنفيذ، والمساهمة في النهاية في النقاش الأوسع حول الاستدامة والابتكار في ممارسات إدارة المشاريع مما يساهم في تحقيق مستهدفات رؤية المملكة 2030 للارتقاء بجودة الحياة وتحسين المشهد الحضري.

كجزء من منهجية البحث، سيتم إجراء مقابلات شبه منظمة مع أصحاب المصلحة الرئيسيين في المشروع، بما في ذلك مدراء المشاريع ومتخصصو الذكاء الاصطناعي ومسؤولو أمانة مدينة جدة، لاكتساب رؤية أعمق حول عيوب طريقة الرصد التقليدية للتشوه البصري، معرفة طريقة عمل الأنظمة المستحدثة، فهم المعوقات والتحديات، وذلك من أجل معرفة الأهداف من عملية الرصد وطرق معالجتها. وقد صُممت هذه المقابلات بحيث تكون مفتوحة وموجهة بأهداف بحثية محددة، مما يسمح بالنقاط طيف واسع من وجهات النظر حول دور الذكاء الاصطناعي في إدارة المشاريع ضمن سياق جودة البيئة الحضرية. مكننا هذا النهج من الكشف عن تفاصيل دقيقة حول التحديات والفرص التي تمت مواجهتها في الاستفادة من الذكاء الاصطناعي لإدارة التشوه البصري، وبالتالي إثراء الفهم للآثار

العملية وفعالية الاستراتيجيات التي يحركها الذكاء الاصطناعي في بيئات العالم الحقيقي. ومن خلال هذه المحادثات، تم جمع روايات مباشرة وآراء خبراء لا تقدر بثمن ساهمت بشكل كبير في عمق واتساع نطاق تحليل دراسة الحالة الخاصة بنا.

توظف الدراسة تحليل الوثائق المتعلقة بالأنظمة المستخدمة للرصد من أجل دراسة وتقييم منهجية الهيئة السعودية للبيانات والذكاء الاصطناعي (سدايا) القائمة على الذكاء الاصطناعي في التفتيش واكتشاف التشوه البصري في أمانة مدينة جدة بشكل نقدي. سيتم تحليل الوثائق المتعلقة بنشر النظام ونتائج التفتيش وأداء المفتشين وإنفاذ الغرامات عبر موقع "إفاء" الحكومي. سيركز هذا التحليل على فعالية تحديد أوجه التشوه البصري والمتسببين من خلال التدقيق في الأطر التكنولوجية والإجرائية المستخدمة، سيكشف البحث عن التطبيقات العملية للذكاء الاصطناعي في الحوكمة البيئية، والأهم من ذلك، يقدم تقييماً نقدياً للاستراتيجيات المستخدمة لمكافحة التشوه البصري، وقد يوجه التحسينات المستقبلية.

بالإضافة إلى ذلك، تتضمن منهجية البحث تحليل التقارير الدورية التي يتم إنشاؤها أثناء تطبيق النظام الجديد لإدارة التشوه البصري في أمانة مدينة جدة ومقارنتها بمثيلاتها في طرق الرصد القديمة. تعتبر هذه التقارير بالغة الأهمية لفهم الفعالية التشغيلية والتحديات التي تمت مواجهتها مع النظام الذي يحركه الذكاء الاصطناعي، بما في ذلك القضايا المتعلقة بدقة الاكتشاف، وعيوب الآلة، والعوامل البيئية مثل الظروف الجوية. من خلال التدقيق في هذه التقارير، نهدف إلى تحديد الأنماط والقضايا المتكررة والأسباب في حصول التشوه البصري والتي قد تؤثر على كفاءة النظام والإدارة الشاملة للتلوث البصري وتقديم بعض المقترحات لتحسينها وبحثها مستقبلاً.

يمكن هذا التحليل من تقييم موثوقية ومتانة التكنولوجيا في مختلف السياقات الحضرية والبيئية، وتقديم رؤى حول كيفية تكيف النظام مع المتغيرات الخارجية مثل التغيرات المناخية وإدارتها، والتي يمكن أن تؤثر بشكل كبير على قدرات الكشف. من خلال هذه المراجعة الشاملة، نعتزم تسليط الضوء على مجالات التحسين في البنية التحتية التكنولوجية والبروتوكولات التشغيلية، لضمان قدرة نظام الذكاء الاصطناعي على المساهمة بشكل فعال في رصد ومعالجة التشوه البصري بشكل فعال. علاوة على ذلك، فإن فهم هذه الديناميكيات سيوفر ملاحظات قيمة لمتخصصي الذكاء الاصطناعي ومديري المشاريع وصناع القرار، مما يسهل تحسين تطبيقات الذكاء الاصطناعي في الإدارة الحضرية والمساهمة في تطوير أنظمة مراقبة بيئية أكثر مرونة وقابلية للتكيف.

7. الإطار العملي: أدوات الرصد والتحليل باستخدام تقنيات الذكاء الاصطناعي

في هذا الجزء، سيتم استعراض ومقارنة بين الأساليب التقليدية لرصد مخالفات التشوه البصري والأساليب الحديثة التي تعتمد على تقنيات الذكاء الاصطناعي. سيتم استعراض الممارسات التقليدية التي كانت تُستخدم في أمانة مدينة جدة، والتحديات التي واجهتها هذه الأساليب من حيث الدقة والكفاءة والسرعة. بالإضافة إلى ذلك، سيتم

تسليط الضوء على الحلول التكنولوجية الحديثة مثل منصة ممثّل وتطبيق بلدي لنس، ودورها في تحسين عمليات الرصد والمتابعة.

سيتناول هذا الجزء أيضًا دور الهيئة السعودية للبيانات والذكاء الاصطناعي (سدايا) في تطوير أنظمة الرصد وتحليل البيانات لتحسين المشهد الحضري. كما سيتم مناقشة دور غرفة عمليات التشوه البصري في أمانة مدينة جدة في متابعة وتنفيذ عمليات الرصد والإغلاق باستخدام التقنيات الحديثة. ومن خلال هذا الجزء، سيتم تقديم رؤية شاملة حول كيفية تطور طرق رصد التشوه البصري من الأساليب التقليدية إلى الحلول الذكية، وتقييم الفعالية والتحسينات التي طرأت على عمليات الرصد بفضل التقنيات الحديثة.

7.1. الممارسات التقليدية لرصد مخالفات التشوه البصري

تضمنت الممارسات التقليدية في أمانة مدينة جدة والبلديات التابعة لها قبل الاستفادة من تقنيات الذكاء الاصطناعي للكشف عن التشوه البصري إجراء مسوحات وجولات رقابية من قبل المفتشين المعيّنين، والاعتماد على شكاوى العامة عن طريق تطبيق بلدي، واستخدام الأدلة الفوتوغرافية، وتعبئة الاستمارات الورقية أو الأنظمة الإلكترونية في كل أمانة على حدة للإبلاغ عن التشوه البصري. هذه الأساليب عادة تكون بحاجة لجهد في جدولة المهام وتحديد الأولويات، وتوزيع المفتشين على المناطق ذات الأولوية أو التي تتطلب وقت ليطم تغطيتها جغرافيا. كما أن فعالية الكشف وإدارة التشوه البصري تكون معتمدة بشكل كبير على الملاحظة والتقارير البشرية والتي يمكن أن تتأثر بالانحيازية وكفاءة المفتشين وخبرتهم في تقييم المخالفة. ويتم التعامل مع البيانات المجمعة حول التشوه البصري عادةً من خلال الإدخال والتحليل اليدوي باستخدام برنامج مايكروسوفت إكسل. ويشمل هذا الإجراء عدة خطوات وهي:

1. جمع البيانات: يقوم المفتشون بتعبئة سجلات الرصد اليومية بتفاصيل رصد التشوه البصري.
2. إدخال البيانات: يتم إدخال المعلومات التي تم جمعها يدويًا في جدول البيانات، حيث يُسجل كل رصد على حدة، ويتم تصنيفها حسب النوع و البلدية التابع لها والموقع.
3. التنظيم: يتم تنظيم البيانات داخل جدول البيانات في جداول وتصنيفها لتسهيل الفرز والتصنيف.
4. التحليل: باستخدام الوظائف المدمجة في إكسل، يمكن تحليل البيانات لتلخيص المعلومات، مثل حساب إحصائيات الرصد، تحديد أكثر أنواع التشوه البصري شيوعًا، أو تحديد تكرار الرصد في مناطق مختلفة.
5. التقرير: يتم تجميع نتائج التحليل في تقارير، والتي تشمل جداول ورسوم بيانية تعرض النتائج. تُستخدم هذه التقارير لإطلاع صناع القرار وتوجيه جهود التصحيح.
6. المشاركة والتواصل: يتم مشاركة ملفات إكسل أو التقارير مع أصحاب المصلحة ذوي العلاقة عبر البريد الإلكتروني، أو النسخ المطبوعة، أو العروض التقديمية لمناقشة النتائج والتخطيط للإجراءات اللاحقة.

هذا النهج في التعامل مع البيانات يعتمد بشكل كبير على العمليات اليدوية ويكون عرضة للأخطاء البشرية، مثل الخطأ في إدخال البيانات، التحيز من قبل المفتشين، دقة توصيف المشكلة المرصودة، معرفة المتسبب في المخالفة، دقة تحديد الموقع الجغرافي، أو الإغفال أثناء التحليل. بالإضافة إلى ذلك، يمكن أن يكون استهلاكًا للوقت وقد لا يوفر رؤية فورية بسبب التأخير بين جمع البيانات وإدخالها وتحليلها وبناءا عليه يصعب الاستجابة للحالات المرصودة ومعالجتها.

7.2. الرصد والتحليل باستخدام تقنيات الذكاء الاصطناعي:

في هذا الجزء، سيتم استعراض الأدوات والتقنيات المستخدمة في رصد وتحليل التشوه البصري باستخدام تقنيات الذكاء الاصطناعي. سيتم تناول الأنظمة والمنصات التي تم تبنيها، مثل منصة ممثّل وتطبيق بلدي لنس، وكيفية عمل هذه الأدوات في جمع وتحليل البيانات المتعلقة بالتشوه البصري، ولوحة البيانات المرتبطة بكل أداة. سيتم أيضًا تسليط الضوء على الأساليب والبرمجيات المتقدمة التي تتيح تحليل البيانات الضخمة واستخلاص الأنماط المخفية من خلال تعلم الآلة وتحليل البيانات الضخمة. سيتم مناقشة كيفية تطبيق هذه الأدوات في بيئة حضرية معقدة مثل مدينة جدة، والتحديات التي واجهتها خلال التنفيذ وكيف يتم استخدام هذه التقنيات في الرصد الفعال وتحليل التشوه البصري، بالإضافة إلى تقييم كفاءتها مقارنة بالطرق التقليدية.

7.2.1. الهيئة السعودية للبيانات والذكاء الاصطناعي (سدايا)

تسهم الهيئة السعودية للبيانات والذكاء الاصطناعي (سدايا) بوصفها المرجع الوطني لكل ما يتعلق بالبيانات والذكاء الاصطناعي في المملكة في تلبية متطلبات النمو الاقتصادي والديمقراطي الذي تشهده المملكة من خلال تحقيق التنمية الحضرية المستدامة في مختلف مدنها، بما يعزز رخاء وجودة حياة المواطنين والمقيمين، ومن ذلك تحسين المشهد الحضري بالتعاون مع وزارة الشؤون البلدية والقروية والإسكان وأمانة مدينة جدة بتهيئة الأماكن العامة في المدن على نحو يُحسن من مستوى خدماتها تحقيقاً لمستهدفات رؤية المملكة 2030.

واستطاعت "سدايا" أن تعزز من هذا الدور الوطني من خلال إنشاء المنصة الوطنية للمدن الذكية (Smart C) التي تهدف إلى دعم عدة قطاعات حيوية منها القطاع البلدي؛ ليكون لها دور رئيس في دعم أعمال الوزارة في تحسين المشهد الحضري من أي حالات تشوه قد تقع في مختلف مدن المملكة، علاوةً على دورها في دعم أعمال التخطيط ورفع جودة الحياة بما يعزز من أهداف برنامج جودة الحياة أحد برامج رؤية المملكة 2030. (SADAIA, 2022).

كما ذكر التقرير (SADAIA, 2022) توقيع "سدايا" مع الوزارة العام 2023 مذكرة تفاهم تهدف إلى تحقيق الاستفادة القصوى من التقنيات وتحليلات البيانات والذكاء الاصطناعي، وتفعيل مفهوم المدن الذكية بما يُعزز قيادة المملكة في هذا المجال؛ وذلك للوصول إلى الأهداف الاستراتيجية المشتركة في رفع مستوى تقديم الخدمات البلدية والسكنية،

وتحقيق الاستدامة الحضرية في مناطق المملكة كافة خاصة بمدينة جدة. وسعت "سدايا" من خلال هذه المذكرة إلى توظيف الحلول الذكية المختلفة للرصد وتحليلات البيانات ونماذج الذكاء الاصطناعي لديها لدعم مستهدفات الوزارة في تطوير وتوفير منصات المدن الذكية لدعم الأعمال التشغيلية المتعلقة بنظافة المدن ومعالجة التشوه البصري والصحة العامة مع توفير التحليلات المتعلقة بالسكان والتوسع العمراني بما يساندها في رفع مستوى التخطيط والتوزيع للخدمات والارتقاء بجودة الحياة، وتحسين خدمات المدن الذكية من خلال مشاركة الخبرات التقنية وتجارب إثبات المفهوم لمنتجات المدن الذكية للقطاعين البلدي والسكني.

كما أتاحت "سدايا" (خدمة تحسين المشهد الحضري) من خلال تطبيق "توكلنا خدمات"؛ لرفع ومتابعة بلاغات التشوه البصري من خلال التطبيق في خطوة تستهدف فيها اتخاذ منهج جديد في عملية المحافظة على المدن والتخطيط العمراني بما يحقق التفاعل الإيجابي بين السكان ومدنهم التي يعيشون فيها وزيادة التعاون للمحافظة على نظافتها.

كما وقّعت "سدايا" مع أمانة مدينة جدة مذكرة تفاهم خلال العام 2023 تهدف إلى إنشاء معمل (أمانة) لتحليل البيانات، ودعم قرارات الأمانة؛ بهدف رفع جودة الحياة، والإسهام في تطوير أعمالها وخدماتها وأنشطتها المتنوعة، إضافة إلى استخدام الإمكانيات التقنية المتوفرة لدى الهيئة في توظيف أحدث التقنيات والأدوات؛ للإسهام في رفع جودة خدمات القطاع البلدي وتوفير حلول تقنية مبنية على الذكاء الاصطناعي والبيانات لتطوير إدارة المدينة بشكل مستدام. وتركز أعمال معمل (أمانة) على رفع قدرات التحليل والتنبؤ، وتوظيف حلول المدن الذكية وتحليلات البيانات ونماذج الذكاء الاصطناعي من خلال مشاركة الخبرات التقنية وتجارب إثبات المفهوم في حالات الاستخدام لمنتجات المدن الذكية للأمانة. (SADAIA, 2022)

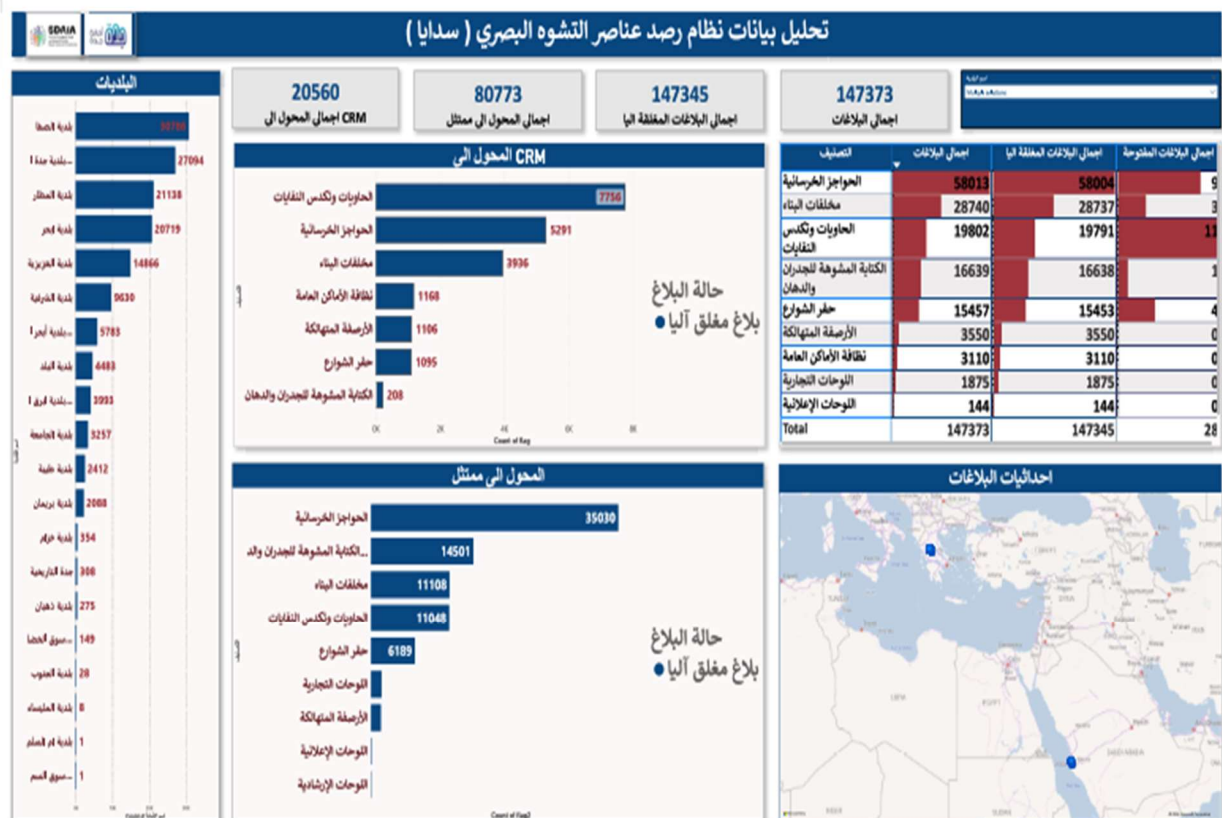
واهتمت "سدايا" بتعزيز مفهوم الشراكة المجتمعية في المحافظة على المشهد الحضري لمدن المملكة وفي مقدمتها العاصمة الرياض إذ أطلقت خلال أعمال القمة العالمية للذكاء الاصطناعي في نسختها الثانية التي عقدت في سبتمبر 2022م تحدي (سمارتاثون) تحت عنوان (تحدي المدن الذكية) بالشراكة الاستراتيجية بين وزارة الشؤون البلدية والقروية والإسكان، والهيئة الملكية لمدينة الرياض، وأمانة منطقة الرياض بهدف تطوير حلول حديثة لتحسين المشهد الحضري بمدن المملكة، والتوصل إلى طرق تقنية تُسهّم في الكشف عن مظاهر التشوه البصري والحد منها باستخدام البيانات والذكاء الاصطناعي. (SADAIA, 2022)

يعرض الشكل (1) نموذج لوحة معلومات نظام سدايا (Dashboard) لرصد عناصر التشوه البصري معلومات شاملة حول البلاغات المتعلقة بالتشوه البصري في المملكة. يبدأ العرض بقائمة على الجانب الأيسر العلوي تظهر الجهات المختلفة المشاركة في البلاغات، مثل أمانة جدة وأمانة الرياض، مع عرض عدد البلاغات لكل جهة. في المنتصف العلوي، يظهر إجمالي عدد البلاغات في النظام، والذي يبلغ 147,345 بلاغاً، مع تقسيم البلاغات إلى

فئات مختلفة تشمل البلاغات المغلقة، وبلاغات غير محددة الموقع، وبلاغات خارج نطاق الأمانات. في القسم الأوسط، يتم عرض البلاغات بحسب حالتها، مثل تجاوزات الباعة الجائلين، الكتابة على الجدران، والنفايات الكبيرة الحجم، مع عدد البلاغات لكل حالة.

على الجانب الأيمن، يتم عرض خريطة توضح توزيع البلاغات حسب المناطق الجغرافية، مما يساعد في تحديد المناطق الأكثر تعرضًا للتشوهات البصرية. أعلاه، يوجد جدول يوضح توزيع البلاغات حسب نوع التشوه البصري وعدد البلاغات لكل نوع، مثل المخلفات الإنشائية، اللوحات الدعائية العشوائية، والإنارة العامة. كما يتم عرض عدد البلاغات التي تم إغلاقها آليًا بالإضافة إلى حالتها من حيث التنفيذ.

توفر لوحة المعلومات نظرة شاملة ومفصلة على حالة التشوه البصري في مدينة جدة وتساعد الجهات المختصة في إدارة وتحليل البيانات بفعالية. من خلال استخدام الأدوات التحليلية المتقدمة، تساهم اللوحة في تحسين عملية صنع القرار وتخصيص الموارد بشكل أفضل لمكافحة التشوهات البصرية، مما يعزز من جودة البيئة الحضرية ويساهم في تحقيق أهداف التنمية المستدامة المتوقعة من رؤية المملكة 2030.

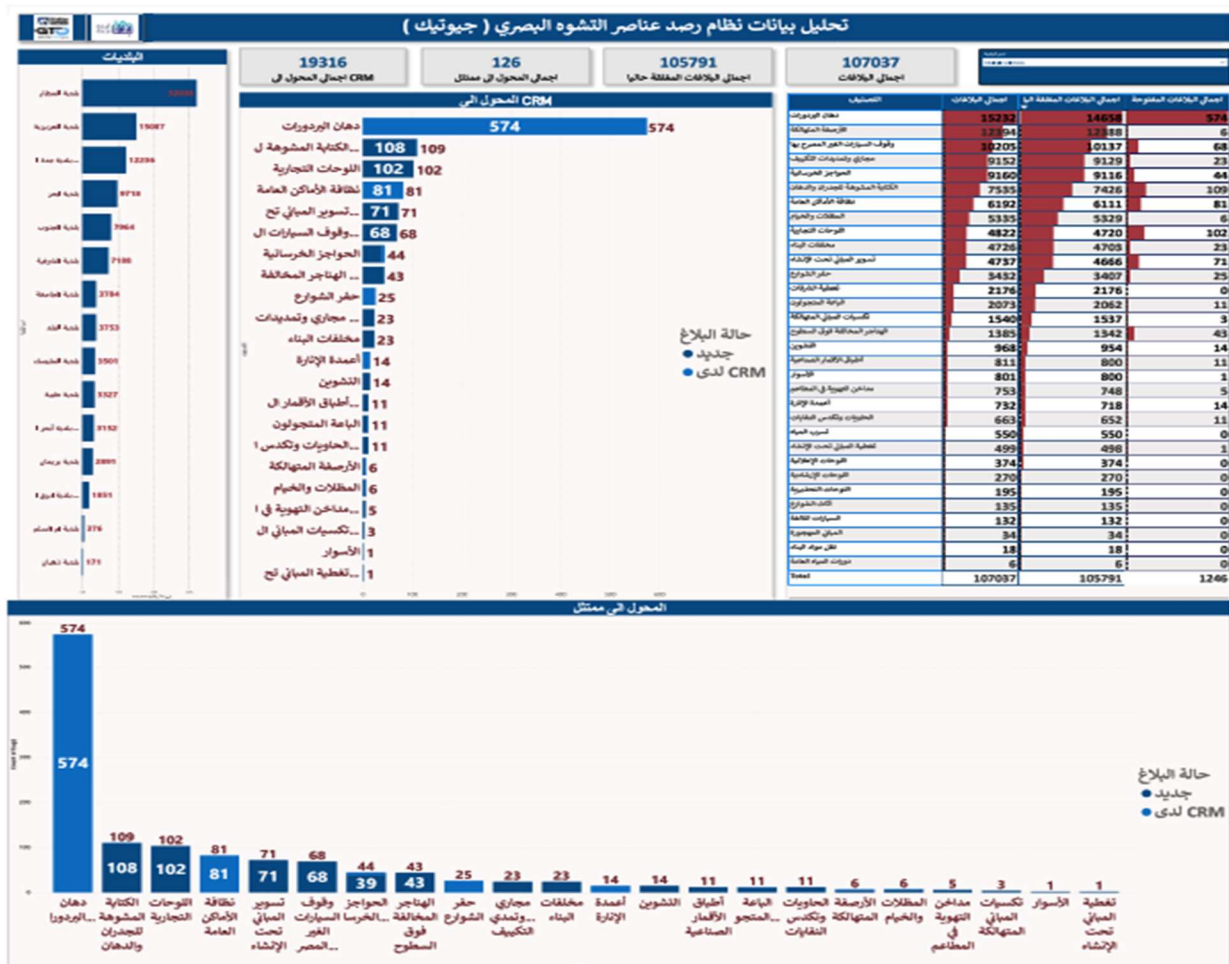


شكل 1: لوحة بيانات نظام سدايا (المصدر: منصة سدايا)

7.2.2. جيوتيك (الرصد الآلي) لعناصر التشوه البصري:

قامت "جيوتك" على إيجاد حلول تقنية لرصد مظاهر التشوه البصري في مدينة جدة؛ لتحسين المشهد الحضري في المدينة، حيث تغطي كامل المدينة بشكل دوري باستخدام كاميرا درون ، كما عملت على تطوير حلول ونماذج الذكاء الاصطناعي لأتمتة عمليات الرقابة في الكشف عن مظاهر التشوه البصري من خلال إرسال البيانات المرصودة إلى وزارة الشؤون البلدية والقروية والإسكان؛ لدعم أعمالها الرقابية في الميدان ومعالجة أماكن التشوه البصري.

تعرض لوحة البيانات الخاصة بنظام جيوتك (شكل 2) وهي مشابهة لما تم شرحه في الشكل 1. تظهر اللوحة إجمالي عدد البلاغات في النظام والذي يبلغ 105,791 بلاغاً، مع تقسيم البلاغات إلى البلاغات المغلقة، وبلاغات غير محددة الموقع، وبلاغات خارج نطاق الأمانات. في القسم الأوسط، يتم عرض البلاغات بحسب حالتها مثل تجاوزات الباعة الجائلين، الكتابة على الجدران، والنفايات الكبيرة الحجم، مع توضيح حالة اغلاق البلاغ.



شكل 2: لوحة بيانات نظام جيوتك (المصدر: منصة جيوتك)

7.2.3. عيوب طريقة الرصد بالذكاء الاصطناعي باستخدام سدايا وجيوتك وأبرز الملاحظات:

بالاطلاع على التقارير الدورية التي تصدرها الامانة عن عمليات الرصد فإنه تم رصد بعض الملاحظات على انظمة الرصد باستخدام تقنيات الذكاء الاصطناعي وتشمل هذه الملاحظات:

1. عدم وضوح بعض صور الحاويات لمعرفة الناقل ليتم توجيه الناقل بالمعالجه.
2. وجود بلاغات جديدة لحالات قديمة تبين عند الوقوف الميداني انه تم معالجتها.
3. وجود بلاغات على حاويات غير ممثلة ، حيث مازال النظام لا يميز بين الحاويات الممتلئة والغير ممثلة.
4. تكرار نفس البلاغ والملاحظة بأرقام مختلفة.
5. عدم وضوح صور بعض البلاغات المرفقة.
6. رصد بعض الحواجز على أنها نفايات.
7. رصد أشخاص على أنهم عناصر من التشوه.

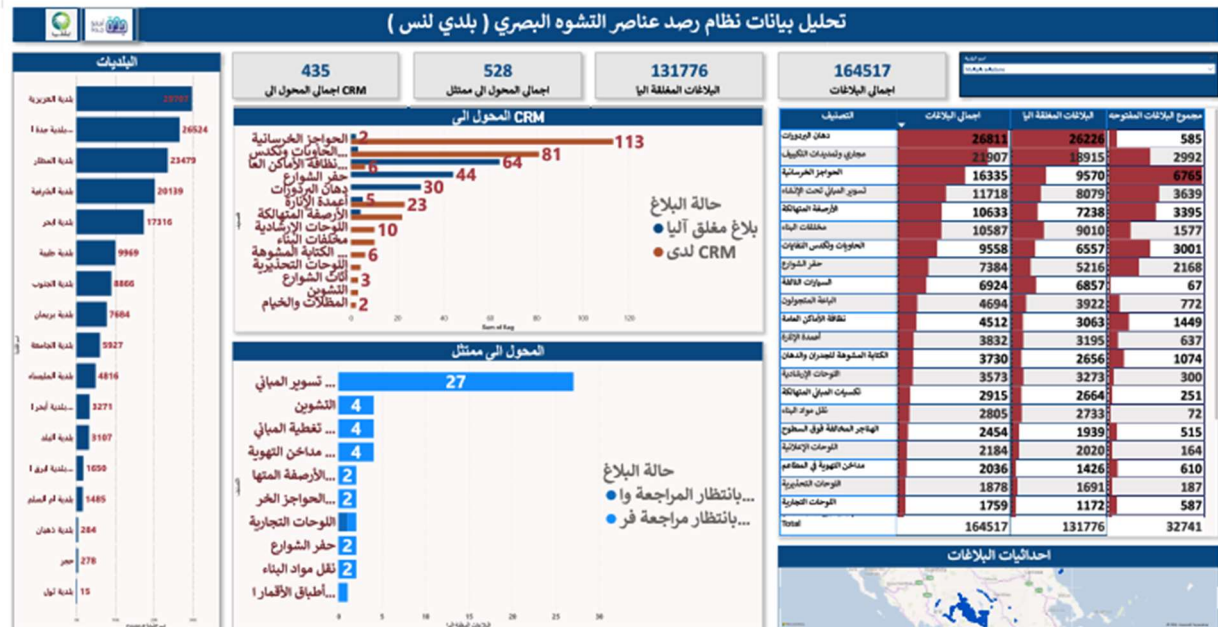
7.2.4. تطبيق بلدي لنس:

عملت "سدايا" على إيجاد حلول تقنية لرصد مظاهر التشوه البصري في مدينة جدة؛ وفقاً لما جاء في دليل "تطبيق بلدي لنس" (2023) عن طريق الاستكشاف الآلي حيث يمكن تدريب خوارزميات الذكاء الاصطناعي عبر تقنية Machine Learning على التعرف على أنواع مختلفة من التشوه البصري وتصنيفها في الصور أو مقاطع الفيديو باستخدام تقنيات مثل استكشاف الاشياء Object detection و تجزئة الصور image segmentation . يتم تغطية كامل المدينة بشكل دوري باستخدام أسطول مركبات مجهزة بكاميرات عالية الدقة (Dash Cams) لبناء تمثيل رقمي للمدينة، كما عملت على تطوير حلول ونماذج الذكاء الاصطناعي لأتمتة عمليات الرقابة في الكشف عن مظاهر التشوه البصري من خلال إرسال البيانات المرصودة إلى وزارة الشؤون البلدية والقروية والإسكان عبر منصة ممثلة؛ لدعم أعمالها الرقابية في الميدان ومعالجة أماكن التشوه البصري. تم تطوير تطبيق بلدي لنس ليتم استغلال اجهزة الجوال لتقوم بعمل الداش كام لرصد مظاهر التشوه البصري ومساعدة الأمانات من أجل رصده ومعالجته. يعرض الشكل (3) لوحة بيانات الرصد عبر تطبيق بلدي لنس والتي تم مناقشتها سابقا. من أهداف ومميزات تطبيق بلدي لنس:

1. توفير الوقت والجهد لعملية رصد عناصر التشوه البصري بالاعتماد على عدد مراقبين اقل، كما انه لا يتطلب أي تدخل من المراقب أثناء عملية الرصد.
2. توفير جميع المعلومات وعمليات الرصد بشكل مباشر للأمانة من خلال توفير خريطة تفاعلية.
3. التقاط الصور الإيجابية والسلبية بشكل تلقائي.

4. زيادة نسبة التغطية للنطاقات ذات الأولوية لرصد عناصر التشوه البصري عن طريق التقاط صورة بمعدل صورة لكل 25 متر.

5. متابعة أداء المراقبين بصورة حية ومباشرة عن طريق تحديد موقع المراقب بتقنيات عالية الدقة من خلال الاعتماد على الأقمار الصناعية.



شكل 3: لوحة بيانات نظام بلدي لنس (المصدر: منصة سدايا)

7.2.5. منصة ممثلة للرقابة لعناصر التشوه البصري:

هي منصة مركزية تابعة لوزارة الشؤون البلدية والقروية والهدف منها هو إدارة جميع عمليات الرقابة البلدية بأنواعها المختلفة على مستوى الأمانات والبلديات، تتضمن أتمتة كامل دورة عمل الرقابة البلدية من خلال مجموعة من الإجراءات والإعدادات المرنة القابلة للتعديل حسب احتياجات كل أمانة وبلدية أو مقدم الخدمة من القطاع الخاص. تهدف المبادرة الى إزالة عناصر التشوه البصري الأكثر شيوعا في المدن وتستهدف جميع سكان المملكة العربية السعودية وتساهم في تحسين المشهد البصري. ومن المتوقع من المبادرة تقليص عناصر التشوه البصري عن طريق إزالة مخلفات البناء، تحسين مظهر حاويات النفايات، إزالة اللوحات التجارية المخالفة، إزالة السيارات التالفة..... إلخ، وتنفيذ حملات تفتيشية من حين لآخر، وتنفيذ حملات للشراكة المجتمعية للمشاركة في إزالة بعض هذه العناصر وتنفيذ مشاريع تحسين عمراني لمحاور الحركة في المدن. ويبرز الهدف من تطبيق ممثل للرقابة الموحدة هو تفعيل دور البلديات في سرعة رصد مخالفات المنشآت المختلفة من خلال الزيارات التفتيشية التي ينفذها المراقبون وإحالتها إلى الإدارة المعنية بالبلدية ثم إلى رئيس البلدية لمراجعة واعتماد هذه المخالفات.

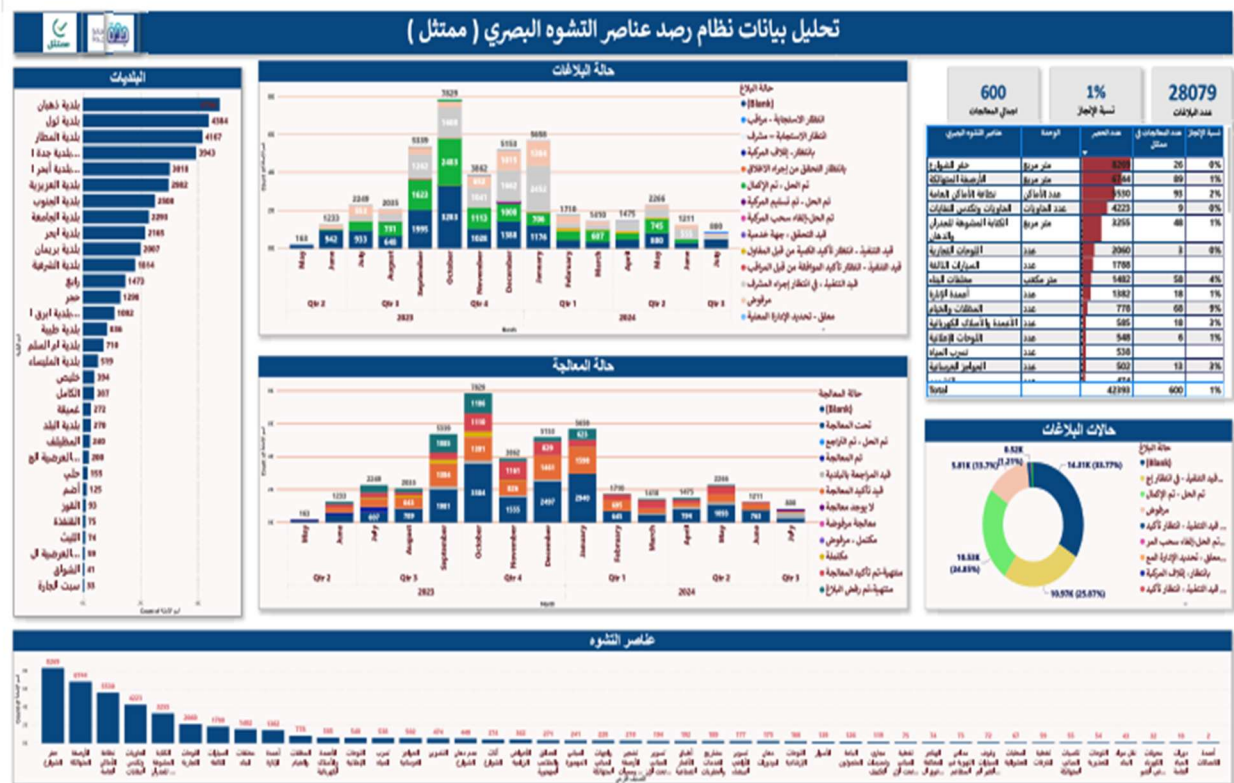
كما توفر المنصة ثلاث محركات رئيسية وهي محرك التجميع، محرك الأولويات ومحرك تحديد المخالف. تعمل هذه المحركات عن طريق أداة الذكاء الاصطناعي المعروفة بنظام تحليل البيانات الضخمة (Big data analysis) وقد تم ربطها بالجهات ذات العلاقة لتسهيل عملة تحديد هوية المخالف. تقوم المحركات بناءً على البيانات الواردة من الرصد الآلي من تحديد المتسبب في المخالفة بالرجوع مثلاً إلى هوية مالك العقار أو السجل التجاري أو رخص الحفر أو البناء، ثم يقوم النظام بتسجيل هوية المخالف ومن ثم تحويل المخالفة لمنصة إيفاء وإغلاق المخالفة آلياً. وفي حال عدم قدرة النظام على تحديد المتسبب أو عدم وضوح أي بيانات تخص الرصد، يتم تحويل المخالفة إلى منصة بلدي ليتم التحقق عن طريق المراقبين الميدانيين. ومن أهداف ومميزات منصة ممثل للرقابة البلدية :

1. رفع كفاءة أداء عمليات الرقابة من خلال رقمنة ونمذجة جميع إجراءات الرقابة بجميع عملياتها وأنواعها على مستوى القطاع البلدي.
2. تفعيل دور البلديات في سرعة رصد مخالفات المنشآت المختلفة من خلال الزيارات التفتيشية التي ينفذها المراقبون وإحالتها إلى الإدارة المعنية.
3. تمكين الأمانات والبلديات ومقدمي الخدمات من إعداد جميع عمليات أنواع الرقابة حسب معايير مرنة خاصة تحقق متطلباتها بما يتماشى مع تطلعات وزارة الشؤون البلدية والقروية.
4. تزويد متخذي القرار بمختلف مستوياتهم الإدارية بمؤشرات الأداء والتقارير التي تساعد في مراقبة وتطوير عمليات الرقابة.

يعرض الشكل (4) لوحة معلومات منصة ممثلة والتي تقدم تحليلاً شاملاً لبيانات رصد عناصر التشوه البصري لكامل المدينة. تبدأ اللوحة بعرض قائمة على الجانب الأيسر تظهر الجهات المختلفة المشاركة في البلاغات، مثل أمانة جدة وأمانة الرياض، مع عدد البلاغات لكل جهة. في الجزء العلوي من الوسط، يتم عرض حالة البلاغات بشكل تراكمي حسب الفصول الزمنية للسنوات المختلفة، حيث توضح الرسوم البيانية توزيع البلاغات بناءً على نوع التشوه البصري. إلى اليمين، يظهر ملخص لإجمالي عدد البلاغات (28,079 بلاغاً) مع تقسيمها إلى البلاغات المغلقة، والتي تحت الإجراءات، والبلاغات الجديدة، بالإضافة إلى نسبة الإنجاز الإجمالية (1%).

تحت الجزء العلوي، يتم عرض حالة النظافة بنفس الطريقة، حيث يتم تحليل بيانات البلاغات المتعلقة بالنظافة عبر الزمن، مما يسهل فهم التغيرات الموسمية والاتجاهات. أسفل اللوحة، يتم عرض عناصر التشوه البصري بشكل مفصل، مع رسم بياني يوضح عدد البلاغات لكل نوع من أنواع التشوه البصري. على الجانب الأيمن السفلي، يوجد رسم دائري يوضح حالة البلاغات بنسبة مئوية لكل حالة (مغلقة، تحت الإجراءات، جديدة)، مما يساعد في تقييم الأداء العام للمنصة في معالجة البلاغات.

تساهم هذه اللوحة في تقديم نظرة شاملة ومفصلة حول حالة التشوه البصري في المدن المختلفة، مما يساعد الجهات المختصة في اتخاذ قرارات مستنيرة لتحسين البيئة الحضرية. استخدام الأدوات التحليلية المتقدمة في لوحة معلومات منصة ممثّل يعزز من فعالية إدارة الموارد ويساعد في تحقيق أهداف التنمية المستدامة من خلال تحسين جودة الحياة للسكان.



شكل 4: لوحة بيانات نظام بلدي لنس (المصدر: منصة ممثّل)

7.2.6. دور غرفة عمليات التشوه البصري في أمانة مدينة جدة:

تقوم غرفة عمليات التشوه البصري بمتابعة عمليات الرصد والإغلاق على مستوى الأمانة. حيث تبدأ عملية إدارة التشوه البصري بالخطوة الأولى والتي تتمثل في استخدام تقنيات الذكاء الاصطناعي في الرصد والنقاط المخالفات المحتملة. بعد ذلك، يتم الإبلاغ عن هذه المخالفات من خلال منصة ممثّل حيث تمر بعملية تصنيف عن طريق الثلاث محركات السابق ذكرها، ثم يتم توزيع الشكاوى إلى الأنظمة الداخلية للأمانة استنادًا إلى طبيعة التشوه البصري. ثم تقوم لجنة مخصصة في كل بلدية بمراجعة واعتماد تفاصيل التشوه المبلغ عنه. يتم بعد ذلك رفعها على منصة إيفاء، ويتم إخطار المخالف بالمخالفة، بما في ذلك إجراءات الدفع أو المعالجة الإضافية من قبل البلدية في حالة عدم القدرة على تحديد هويته. وتختتم العملية بفحص الجودة، المتضمن زيارة متابعة إن لزم للتأكد من حل المشكلة، وينتهي بإغلاق الرصد.

كما يتم في غرفة العمليات تحليل بيانات نظام رصد عناصر التشوه البصري عن طريق سحب البيانات الخاصة بالرصد الذكي من قبل تقنيات الذكاء الاصطناعي من أجل إنشاء لوحة بيانات (الشكل 1) الأمر الذي لم يكن متوفر من البيانات الناتجة من طريقة الرصد التقليدية. توفر لوحة البيانات رؤية شاملة ومفصلة لعمليات الرصد وعرضها بشكل بصري سهل الفهم يساعد في تسهيل عملية صنع القرار من خلال تقديم ملخصات واضحة ودقيقة تقود إلى قرارات مبنية على البيانات الفعلية. كما تعمل على تحسين الكفاءة بتقليل الحاجة لتقارير معقدة وطويلة، مما يسمح بالوصول السريع للمعلومات. لوحة البيانات مهمة أيضاً في المراقبة المستمرة للأداء للبلديات الفرعية، وتُعدّ أساسية للاستجابة للتغيرات وتعديل الاستراتيجيات للتعامل مع نتائج الرصد عند الضرورة، وكذلك تربط بين الأهداف الاستراتيجية والأداء اليومي وتوزيع الموارد حسب الحاجة، مما يعزز التركيز على المبادرات التي تدعم اتخاذ القرارات وتحقيق هذه الأهداف اليومي وتوزيع الموارد حسب الحاجة، مما يعزز التركيز على المبادرات التي تدعم اتخاذ القرارات وتحقيق هذه الأهداف.

8. الحدود المكانية والزمانية للدراسة:

استهدفت الدراسة مدينة جدة وهي من أكبر المدن داخل المملكة العربية السعودية. وتعتبر واحدة من أبرز المدن في المملكة العربية السعودية وتقف على أعتاب فرصة ذهبية للتحويل إلى مدينة ذكية رائدة من خلال استغلال الذكاء الاصطناعي. حيث يمكن لتقنيات الذكاء الاصطناعي أن تسهم في تطوير مدينة جدة، ليس فقط لتحسين البنية التحتية والخدمات، ولكن أيضاً لتعزيز مكانتها كمدينة مستدامة وذكية تستجيب لاحتياجات سكانها وتواجه التحديات المستقبلية بفعالية. وقد اقتصرَت الدراسة على الممارسات المتعلقة بالأنظمة المستخدمة للرصد من أجل دراسة وتقييم منهجية الهيئة السعودية للبيانات والذكاء الاصطناعي (سدايا) القائمة على الذكاء الاصطناعي في التفتيش واكتشاف التشوه البصري في أمانة مدينة جدة في عامي 2023 إلى 2024.

9. التحليل والنتائج:

تؤكد الدراسة الإمكانيات والفعالية العالية للذكاء الاصطناعي في اكتشاف وتصنيف الملوثات البصرية من صور الطرق العامة رغم وجود بعض التحديات مثل دقة رصد المخالفات والتحقق من المخالفة والمخالف و الأتمتة الكاملة وعامل الوقت أيضاً وغيرها من التحديات التي تمت الإشارة لها، إلا أن التطبيقات المستخدمة حالياً أثبتت جدارتها مع التأكيد على الحاجة إلى دمج حلول الذكاء الاصطناعي في التخطيط الحضري وممارسات الإدارة البيئية من أجل التنمية الحضرية المستدامة.

تم تحديد 5 تصنيفات أساسية لعناصر التشوه البصري من قبل وزارة الشؤون البلدية والقروية وهي الطرق والشوارع، الإنارة والمرافق الخدمية واللوحات، المباني، الحدائق والفراغات العامة. و يندرج تحته هذه التصنيفات 43 تصنيف فرعي لعناصر التشوه البصري. يتم رصد جميع هذه البنود عن طريق تطبيق بلدي لنس

وذلك بسبب سرعة وكفاءة الرصد عن طريق التسجيل المباشر بواسطة كاميرات الداش كام، بينما يتم رصد 10 عناصر من التصنيف الفرعي بواسطة نظام سدايا و 32 عنصر بواسطة نظام جيوتك وذلك طبقاً لإمكانيات الانظمة.

9.1 نتائج الرصد التقليدية:

تقوم غرفة عمليات التشوه البصري بجمع البيانات التي يتم رصدها من قبل مفتشين الأمانة والبلديات الفرعية التابعة لها بشكل أسبوعي عن طريق نموذج موحد في برنامج الاكسل تم إعداده وتوزيعه بواسطة غرفة عمليات التشوه البصري لسهولة الحصول على البيانات. يحتوي الجدول على بيانات الرصد الاساسية وتشمل البلدية الفرعية، الحي، عنصر التشوه البصري المرصود ووحدة قياسه، بالإضافة الى إجمالي أعداد العناصر المرصودة وحالة الإغلاق. في المقابل يفترض النموذج لمعلومات الراصد، احداثيات الرصد، صور الحالة المرصودة مما يصعب عملية متابعة المفتشين والحصول على المعلومات اللازمة في حال الحاجة للرجوع لموقع المخالفة أو المفتش الذي قام بالرصد. ايضاً لا يحتوي الملف على وقت وتاريخ رصد المخالفة، وقت وتاريخ إغلاقها وذلك ليتم حساب الزمن المستغرق في إغلاق المخالفات وبالتالي حساب كفاءة الرصد والاغلاق.

بالإضافة الى ماسبق ومن خلال اجراء المقابلات تبين ان البيانات المدخلة يدوياً، خاصة بكميات كبيرة وتفاصيل متعددة، يمكن أن تشكل تحدي في إدارتها والتعامل معها وذلك بسبب عدة عيوب تؤثر على جودة البيانات وكفاءتها والفعالية العامة لعمليات إدارة وتحليل البيانات مثل:

1. عرضة للخطأ البشري: الإدخال اليدوي للبيانات يكون عالي الحساسية للأخطاء، بما في ذلك الأخطاء الطباعية، التكرارات، الحذف، أو عدم الدقة. هذه الأخطاء يمكن أن تؤدي إلى بيانات غير موثوقة، مما يؤثر على التحليلات واتخاذ القرارات.
2. يستغرق وقتاً طويلاً ويتطلب جهداً كبيراً: يتطلب إدخال البيانات يدوياً وقتاً وجهداً كبيرين، مما يجعله عملية غير فعالة، خاصة بالنسبة لمجموعات البيانات الكبيرة والمعقدة نسبياً. هذا يمكن أن يؤخر توفر البيانات للتحليل واتخاذ القرارات.
3. مكلف: غالباً ما يتطلب الإدخال اليدوي للبيانات المزيد من الأفراد، مما يزيد من تكاليف العمل. بالنسبة للمشاريع الكبيرة النطاق، يمكن أن يكون هذا أكثر تكلفة بكثير من العمليات الآلية.
4. مشاكل في التوسع: مع نمو حجم البيانات، تصبح عملية الإدخال اليدوي أكثر صعوبة في الإدارة وغير فعالة. من الصعب توسيع العمليات اليدوية لتلبية متطلبات مجموعات البيانات الكبيرة.
5. قدرة محدودة على تحليل البيانات: يمكن أن يعيق إدارة البيانات يدوياً القدرة على أداء تحليلات معقدة، خاصة عند التعامل مع مجموعات بيانات كبيرة. بالمقارنة، يمكن للأنظمة الآلية معالجة البيانات وتحليلها بسرعة، مما يكشف عن اتجاهات ورؤى تساعد في اتخاذ القرارات والتي لا يمكن أن توفرها العمليات اليدوية.

6. تحديات الاتساق والتوحيد للبيانات: ضمان الاتساق والتوحيد عبر البيانات المدخلة يدويًا يعتبر تحديًا، حيث يمكن أن يكون لدى الأفراد تفسيرات مختلفة لكيفية تسجيل البيانات. يمكن أن يؤدي هذا إلى عدم اتساق يعقد التحليل ويتطلب جدها لتصحيحها.
7. صعوبة في التحديث والصيانة وحفظ البيانات: يمكن أن يكون تحديث وصيانة البيانات يدويًا أمرًا معقدًا عرضة للأخطاء. يمكن للأنظمة الآلية تتبع التغييرات والتحديثات والحفظ بسهولة أكبر، مما يضمن بقاء البيانات حديثة ودقيقة.
8. قيود الوصول والمشاركة: قد لا تكون البيانات المدخلة يدويًا في نظام واحد سهلة الوصول أو متوافقة مع أنظمة أخرى، مما يجعل من الصعب مشاركة البيانات أو دمجها عبر المنصات أو مع أصحاب المصلحة الآخرين.
9. مخاطر الأمان والامتثال: قد لا تمثل عمليات إدخال البيانات يدويًا دائمًا للوائح حماية البيانات والخصوصية، مما قد يؤدي إلى ثغرات أمنية ومشاكل قانونية.

9.2. نتائج الرصد باستخدام تقنيات الذكاء الاصطناعي:

إن الانتقال إلى أنظمة إدخال وإدارة البيانات الآلية يمكن أن يساعد في التقليل من عيوب الطريقة التقليدية، حيث يمكن أن تساعد هذه الأنظمة على تحسين الدقة والكفاءة، القابلية للتوسع، الأمان والخصوصية، كما تمكن من إجراء تحليلات متقدمة واكتساب رؤى أكثر تعقيدًا من البيانات تساعد في إدارة عمليات التشوه البصري بفعالية. كل هذه المميزات توفره التقنيات الحديثة المرتبطة بالذكاء الاصطناعي التي تم مناقشتها مسبقًا، حيث تقوم النماذج والتقنيات المستخدمة في الرصد بتوفير جميع البيانات اللازمة والتي افتقرت لها طريقة الرصد التقليدية مثل أحداثيات الرصد، صور الحالة، معلومات الرصد، مما يساعد في سهولة التعامل مع البيانات الضخمة بواسطة تقنية Big Data، كما وفرت المنصات كما تم مناقشتها سابقًا لوحة بيانات شاملة Dashboard تفاعلية لمتابعة أعمال الرصد داخل الامانة.

ومن أجل توحيد المخرجات وإجراء التحليلات اللازمة للبيانات ليتم الاستفادة بها من قبل الجهات ذات العلاقة، تقوم الجهات الرائدة للتشوه البصري بإدخال البيانات في منصة ممثلة كونها المنصة المركزية التابعة لوزارة الشؤون البلدية والقروية والتي يتم عن طريقها إدارة وامتة جميع عمليات وبيانات الرقابة على مستوى الأمانات والبلديات. كما توفر المنصة إمكانية تخصيص المخرجات وربطها بمؤشرات قياس الأداء و لوحة التحكم (Dashboard) داخل الامانة والتي تساعد أصحاب المصلحة بتقييم الأداء وتحديد الاتجاهات واتخاذ قرارات مستنيرة بناءً على المعلومات المرئية، والذي لا يمكن تحقيقه باستخدام الطرق التقليدية للرصد والتعامل مع البيانات وذلك لمتابعة المستهدفات والأهداف المطلوب تحقيقها من قبل الامانة وذلك من اجل تحقيق مستهدفات رؤية المملكة 2030.

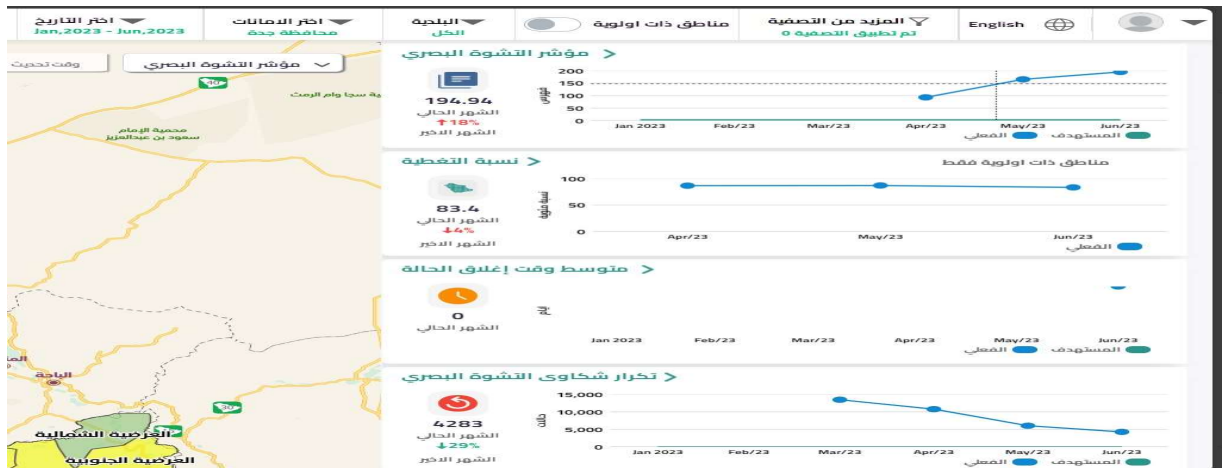
لتحليل نتائج الرصد وفهم أثر تطبيقات الذكاء الاصطناعي على ادارة عمليات رصد التشوه البصري، ومدى فعالية هذه الانظمة مقارنة بطرق الرصد التقليدية، فقد تم استخراج إحصائيات الرصد من منصة ممثّل التابعة لوزارة الشؤون البلدية والقروية وقد تم الاعتماد عليها في مناقشة مخرجات الرصد بسبب ارتباطها بمؤشرات قياس الاداء المتعلقة بأهداف رؤية المملكة 2030.

يحتوي تقرير منصة ممثّل على أربعة مؤشرات رئيسية للتشوه البصري، وهي مؤشر التشوه البصري وهو "مقياس موحد لقياس تأثير التشوه البصري على نطاق المملكة إلى مستوى تحديد صغير يبلغ 1*1 كيلو متر مربع للشبكات الحضرية في جميع أنحاء المملكة"، ومؤشر نسبة التغطية (%)، مؤشر متوسط وقت اغلاق الحالات لتقييم كفاءة الاطراف المسؤولة في معالجة بلاغات التشوه البصري (يوم)، وأخيرا مؤشر تكرار شكاوي التشوه البصري المتكررة داخل نفس المنطقة الجغرافية ذات الخصائص المماثلة (عدد) (MOMRA,2024)

توفر المنصة ايضا خريطة تفاعلية تقدم تمثيلاً بصرياً لمؤشرات التشوه البصري الأربعة، يتم ترميزها بالألوان على الخريطة وهي اللون الأخضر (منخفض)، الاصفر (متوسط)، البرتقالي (مرتفع) واخيرا اللون الاحمر (مرتفع جدا). تساعد الخريطة بشكل سريع على معرفة كفاءة الاستجابة لكل بلدية، حيث يدل اللون الأخضر مثلاً على مناطق الاستجابة السريعة والفعالة، بينما يدل اللون الأحمر على المناطق التي تعاني من تأخير كبير في الاستجابة لشكاوي التشوه البصري. كما يتيح المؤشر الرؤية الواضحة لنسبة تغطية المناطق بالتشوه البصري و معدلات تكرار الشكاوي فيها، مما يساعد متخذي القرار في تحليل الوضع بصورة سريعة وتطوير استراتيجيات لمكافحة التشوه البصري بشكل أكثر فعالية. وحيث ان المنصة تمكن الحصول على بيانات الرصد لفترة لا تزيد عن ستة أشهر، فقد تم تقسيمها إلى ثلاثة فترات رئيسية من أجل تحليل النتائج كما يلي.

9.2.1. الفترة من يناير 2023 إلى يونيو 2023

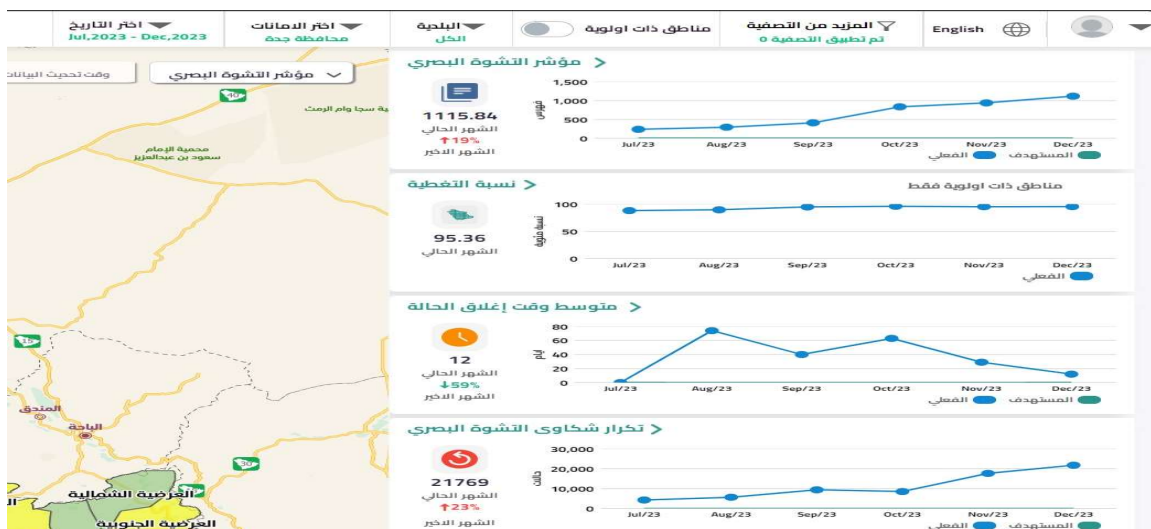
يشير الشكل (5) إلى بداية مؤشر التشوه البصري خلال شهر أبريل وهو وقت بدء استخدام منصة ممثّل، رغم وجود طرق الرصد القديمة. كما يشير الشكل إلى أن معدل تكرار شكاوي بدأ في الانخفاض في مايو مع ارتفاع نسبة الكشف عن التشوه البصري بنسبة 18%، وهو ما يرتبط باستخدام أنظمة الذكاء الاصطناعي سدايا وجيوتك، مع معدل تغطية وصل إلى 83.4 للمناطق ذات الأولوية.



شكل 5: مؤشرات التشوه البصري من يناير 2023 الى يونيو (المصدر: منصة ممتثل) 2023

9.2.2 الفترة من يوليو إلى ديسمبر 2023

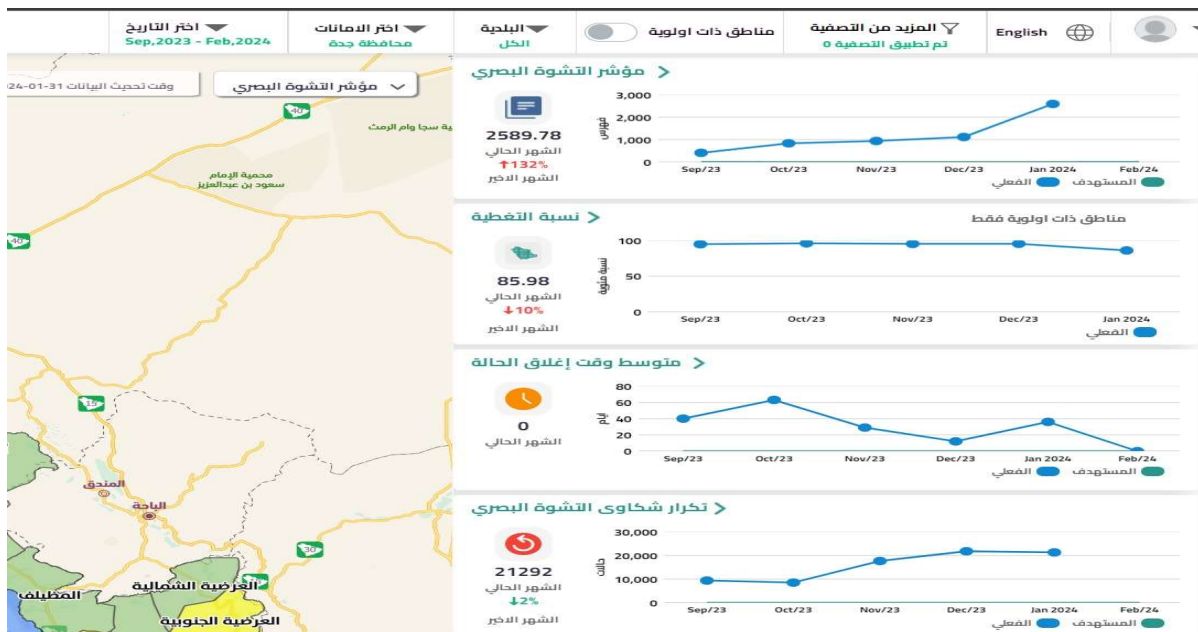
يبين الشكل (6) استمرار مؤشر التشوه البصري في الارتفاع حيث ارتفع المؤشر من 237 في بداية الفترة إلى 1115 في نهايتها، وكذلك ارتفاعا في نسبة التغطية الى 95.36%، و يعود ذلك إلى تحسين قدرات الكشف لدى أنظمة الذكاء الاصطناعي (سدايا وجيوتك) وبالتالي إلى زيادة كفاءة عمليات الرصد. ومع ازدياد حالات الرصد فقد ازداد متوسط وقت الاغلاق للملاحظات ليصل ذروته في شهر أغسطس الأمر الذي يعكس الازدياد الكبير في عدد الحالات المرصودة، ولكنه انخفض بنسبة 59% مع نهاية عام 2023 ليصل إلى أقل من 20 يوم لإغلاق الملاحظات المرصودة، حيث أصبح النظام قادرا على رصد المتسبب المحتمل للمخالفة وإيقاع الغرامة ومن ثم اقبال المخالفة آليا دون الحاجة لإرسال مراقب للموقع.



شكل 6: مؤشرات التشوه البصري من يوليو 2023 الى ديسمبر 2023 (المصدر: منصة ممتثل)

9.2.3. الفترة من سبتمبر 2023 إلى مارس 2024

تشهد الفترة ارتفاعاً مطرداً في مؤشر التشوه البصري (الشكل 7)، يعود على الأرجح، إلى تراكم مستمر لمظاهر التلوث أو تحسينات أكبر في قدرات أنظمة الذكاء الاصطناعي (سدايا وجيوتك). ومع إطلاق أداة الذكاء الاصطناعي الجديدة (بلدي لينز) في يناير ٢٠٢٤، يظهر ارتفاع حاد في المؤشر، إذ يساعد تطبيق بلدي لنس إلى النقاط المزيد من حالات التشوه البصري باستخدام الداش كام. حيث نتج عن ذلك ارتفاع في مؤشر التشوه البصري بنسبة 132%، ورغم ذلك فقد ارتفع معدل وقت إغلاق الحالات إلى 36 يوم مع بدء تطبيق نظام بلدي لنس في شهر يناير لكنه انخفض مرة أخرى مقرباً من الصفر بسبب آلية النظام في تحديد المخالف وإغلاق المخالفة.



شكل 7: مؤشرات التشوه البصري من سبتمبر 2023 إلى مارس 2024 (المصدر: منصة ممثّل)
بناء على تحليل النتائج السابق ذكره فقد توصلت الدراسة إلى أن هناك اختلاف واضح في معدلات الكشف قبل وبعد استخدام أنظمة الذكاء الاصطناعي. حيث ساهم إدخال أنظمة الذكاء الاصطناعي (سدايا وجيوتك) في مايو 2023 إلى زيادة ملحوظة في رصد و اكتشاف التشوه البصري، مما يدل على أن لكل أداة جديدة تأثير على مؤشر التشوه البصري، مع إظهار الأداة الأحدث (بلدي لنس) التأثير الأكثر أهمية مما يدل على فعالية استخدام أدوات الذكاء الاصطناعي وهو ما أكدته الدراسات السابقة، حيث ساهمت منصة ممثّل والمحركات التي تستخدمها في سهولة التعامل مع البيانات الكبيرة وربطها مع الجهات ذات العلاقة من أجل تحديد المتسبب في التشوه البصري، وتشير البيانات أيضاً إلى مساهمة أنظمة الرصد المعتمدة على تقنيات الذكاء الاصطناعي من زيادة كفاءة عمليات الرصد وتقليل الجهد المبذول للرصد مقارنة بطرق الرصد التقليدية .

10. توصيات الدراسة:

1. عمل قاعدة بيانات بين الامانات يتم تزويد نظام ML بها لتحسين عمليات الرصد والفلترة للمخالفات لتقادي رصد الاجسام الغير مرغوبة مثل الاشخاص، الحاويات الغير ممتلئة على سبيل المثال لا الحصر.
2. توحيد شكل بعض الصبات واعمدة الحماية وتغذية النظام بها مثل الموجودة امام المنشآت الخاصة بحيث لا يتم رصدها من قبل النظام
3. بحث إمكانية وضع رمز استجابة سريع QR Code على الحاويات يكون قابل للقراءة من قبل أنظمة الرصد لتحديد هوية مالك الحاوية وسهولة تتبعه.
4. الربط مع وزارة النقل باستخدام أنظمة تتبع المركبات لمراقبة نقل وتفرغ النفايات ومخلفات البناء إلى المرامم الرسمية وذلك من أجل مكافحة أسباب التشوه البصري المتعلقة برمي المخلفات في الاراضي الفضاء.
5. التحقيق في نماذج الذكاء الاصطناعي التي تتجاوز التطبيقات القياسية من أجل التطور والاستدامة البيئية ، لتقييم مزاياها وقيودها.
6. تحليل فوائد وعيوب تنفيذ تقنيات الذكاء الاصطناعي في سياق المدن الذكية بيئيا ، للكشف عن القصور وتحسين الأداء الحالي.
7. دراسة كيف يمكن للمدن الذكية بيئيا تحقيق توازن متناغم بين الأهداف البيئية والاقتصادية والاجتماعية من خلال استخدام تقنيات الذكاء الاصطناعي.
8. يقترح توسيع استخدام الذكاء الاصطناعي في الإدارة البيئية ليشمل مختلف أنواع التلوث، مع الاستفادة من قدرة الذكاء الاصطناعي على معالجة مجموعات البيانات الكبيرة.
9. يقترح توسيع استخدام الذكاء الاصطناعي في الإدارة البيئية ليشمل زيادة قدرة تطبيقات الذكاء الاصطناعي المستخدمة على معالجة مجموعات البيانات الكبيرة.
10. يدعو إلى إجراء أبحاث متعددة التخصصات لتحسين نماذج الذكاء الاصطناعي للأغراض البيئية ، بهدف إيجاد حلول أكثر شمولاً وكفاءة.
11. توسيع نطاق الذكاء الاصطناعي في المراقبة البيئية بحيث تركز البحوث اللاحقة كيف يمكن الجمع بين الذكاء الاصطناعي وتكنولوجيات الاستشعار المتنوعة لتحسين تحديد الملوثات البيئية وفحصها.
12. قد تبحث الدراسات القادمة في كيفية تسخير التقنيات الذكاء الاصطناعي لتحسين دقة تقييمات الهياكل الحضرية وتوقعات جودة الطقس والمساعدة في عمليات صنع القرار المتعلقة بالتنمية البيئية والحفاظ على البيئة.

11. المصادر والمراجع:

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The Limitations of Traditional Construction Quality Management in Large-Scale Infrastructure Projects in Saudi Arabia

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الملخص:

تهدف هذه الدراسة إلى تحليل أوجه القصور الجوهرية في ممارسات إدارة جودة البناء التقليدية (CQM) في مشاريع البنية التحتية واسعة النطاق في المملكة العربية السعودية، في ظل التوسع الكبير الذي يشهده القطاع ضمن مستهدفات رؤية المملكة 2030. واعتمدت الدراسة على منهجية بحثية مزدوجة تجمع بين التحليل النوعي لبيانات مشاريع حقيقية تمتد لسنوات، وتحليل كمي قائم على استبيان موجه إلى مجموعة كبيرة من المتخصصين والمهنيين في قطاع التشييد. تكشف نتائج الدراسة عن وجود تحديات متكررة ومؤثرة ترتبط بفعالية أنظمة الجودة التقليدية، أبرزها طول مدد إغلاق تقارير الملاحظات وعدم المطابقة، وتكرار المشكلات المرتبطة بالمواد وأعمال الحفر والردم، إضافة إلى ضعف الالتزام بالإجراءات والمواصفات المعتمدة. كما أبرزت نتائج الاستبيان إدراكا واسعاً بين المهنيين لقصور الأساليب اليدوية والتقليدية، ووجود استعداد عالٍ لتبني حلول تعتمد على الذكاء الاصطناعي، لما تقدّمه من قدرة على التنبؤ بالمشكلات، وتحسين الرقابة، ورفع مستوى كفاءة إدارة الجودة. وتؤكد الدراسة ضرورة التحول من أنظمة الجودة التقليدية القائمة على التوثيق اليدوي وردود الفعل المتأخرة، إلى أنظمة رقمية تعتمد على البيانات والتحليلات التنبؤية، مما يسهم في تحسين أداء المشاريع، وخفض معدلات الأخطاء وإعادة العمل، ورفع جودة التنفيذ، بما يواكب التوجه العالمي نحو التحول الرقمي في قطاع التشييد.

الكلمات المفتاحية: إدارة جودة البناء، مشاريع البنية التحتية، الذكاء الاصطناعي، مراقبة الجودة، المملكة العربية السعودية.

Abstract

This paper investigates the effectiveness of Construction Quality Management (CQM) Practices in the context of large scale and complex infrastructure projects in Saudi Arabia. The aim is to identify the specific limitations of traditional methodologies and practices used in quality, and to explore the potential of Artificial Intelligence (AI) to address these challenges. A mixed-method approach was used, combining both qualitative analysis of projects data, and insights from a quantitative survey from professional working on the same industry. The analysis reveals significant inefficiencies in traditional CQM practices. Highlighted findings include long resolution times for quality issues, average 91 days for Site Observation reports (SOR) and 101 days for Non-Conformance Reports (NCR), and other issues remaining unresolved for more than a year. The most frequent issues relate to asphaltting works, material management, trenching and excavation, and procedural non-compliance. These issues indicate systematic problems that are not effectively addressed using current CQM practices. The analysis of the survey data complements these findings, with professionals highlighting challenges in defect tracking, compliance with specifications, and implementing corrective and preventive actions. The study also found a high level of interest and readiness among those professionals for adopting AI based solutions to help address those challenges. Overall, the study provides robust real world empirical evidence of the limitations of traditional CQM practices in large scale infrastructure projects. By integrating and interpreting detailed projects data from ongoing infrastructure projects in Saudi Arabia, it offered a comprehensive view of the challenges and provides a strong recommendation and a case for the adoption of AI powered tools to enhance and improve the effectiveness of quality practices and the overall quality outcomes in the construction industry.

Keywords: Construction Quality Management (CQM), Infrastructure Projects, Construction Industry, Artificial Intelligence (AI), Saudi Arabia.

Introduction

Quality management in all industries including construction is fundamental for ensuring that projects consistently meet design specifications, adhere to regulatory requirements, while meeting client expectations. For many years, traditional CQM has been built upon a foundation of methodologies emphasizing adherence to established rules, procedures and measurement of non-conformance and rework (Love et al., 2023). This approach often involves extensive human based manual inspections and manual logging of site observations and nonconformities, and reactive problem solving which can be inefficient and prone to human error. Such methods consume significant time and resources, contributing to project delays and cost overruns due to labor nature of onsite checks and documentation. Furthermore, reliance on human observations introduces subjectivity and the potential for oversight or fatigue, leading to undetected defects (Aichouni et al., 2014).

In Saudi Arabia, some large-scale projects frequently encounter significant time and cost overruns, these traditional quality control methodologies proven particularly inadequate (AlMunifi & Almutairi, 2021). For instance, studies reveal a significant misunderstanding of quality management system strategies among Saudi construction firms, highlighting organizational culture as a major impediment to effective QMS implementation (Aichouni et al., 2014). This underscores the urgent need for innovative quality assurance and control methods that can enhance precision and efficiency, moving beyond the prevalent reliance on traditional approaches and their associated inefficiencies (Toyin & Sattineni, 2025). Despite technological advancements like Building Information Modeling and advanced project management software, the construction sector, particularly in Saudi Arabia, still struggles to fully leverage emerging technologies such as Artificial Intelligence to address persistent challenges in quality management.

With the increase of size and complexity of modern infrastructure projects, the traditional quality control approaches face a growing challenge in maintaining consistent standards. In Saudi Arabia, and since the announcement of its ambitious 2030 Vision, the construction sector has experienced a rapid expansion and huge infrastructure initiatives to support it, project outcomes sometimes reveal deficiencies and weakness during implementation stages due to size and complexity of projects. This paper provides a comprehensive examination of the limitations of these conventional CQM practices, incorporating a thorough literature review, a detailed problem background, and an outline of the research methodology. The study's importance lies in leveraging empirical data from a major infrastructure program in Jeddah to quantify inefficiencies inherent in outdated CQM methods and underscores the critical need for transforming and adoption toward technology driven solutions.

Research Problem

The construction market in the Kingdom of Saudi Arabia considered the largest in the Gulf region, it faces considerable issues related to inefficiency and ineffectiveness in project delivery (AlMunifi & Almutairi, 2021). This is particularly evident in the persistent challenges related to quality, which includes reworks, delays, and cost overruns (Kashif et al., 2022). As project size increases, the volume of data, the number of stakeholders, and the geographic distribution of some infrastructure projects creates a highly challenging environment. In such conditions, traditional CQM practices using manual and paper-based forms, or segmented spreadsheets cannot effectively manage. As a result, several critical issues arise including delayed communication, poor data gathering and availability, inconsistent process implementation, and a reactive rather than proactive approach toward quality control. This leads to persistent quality deficiencies, evidenced by frequent reworks and project delays, which ultimately escalate costs and affect overall project performance (Kashif et al., 2022).

These issues underscore a significant gap between current quality management practices and the desired project outcomes, contributing to suboptimal structural integrity, and safety concerns, and the recurring problem of rework, delays, and cost overruns (Vishe, 2023). The financial implications of these quality failures are substantial, according to Lawani et al. (2022) rework of defective components estimated to constitute 6% to 15% of total construction costs. The contribution of this study to the construction industry and academia is to highlight these major issues in current CQM practices and provide a recommendation and a case for the importance of adoption of modern and digital solutions. These solutions, including AI, can lead to higher quality, reduce costs, and improve safety on construction projects while meeting or exceeding customer expectations. The integration of such technologies moves beyond the limitations of traditional, manual, inspections methods, offering enhanced precision and efficiency in quality assurance and control (Toyin & Sattineni, 2025).

Importance of the Study

This study is particularly significant for the rapidly expanding Saudi construction sector, which despite its substantial market share, often struggles with inadequacies in quality management system implementation and consistent adherence to quality requirements. An empirical study by Aichouni et al. (2014) revealed a clear misunderstanding of Quality Management Systems (QMS) and associated tools among construction firms within the kingdom. Many construction firms still not fully perceive or implementing known quality frameworks such as ISO 9001. This deficiency of applying frameworks often leads to

significant increases in cost of quality, encompassing appraisals, prevention, and internal / external failure costs. As a result, the profitability and competitiveness of construction firms decrease, as well as stakeholders' overall satisfaction. This situation increases the necessity for critical re-evaluation of the existing CQM practices and understand how modern technologies, particularly AI, can moderate the impact of these deficiencies (Khadim et al., 2023).

The overarching goal is to transform traditional, often manual, quality practices which are long associated with inefficiencies into more precise and efficient digital workflows (Toyin & Sattineni, 2025). This transformation is critical for managing the increasing scale and complexity of mega infrastructure projects with optimal quality, efficiency, and cost-effectiveness (Luo et al., 2022; Othman et al., 2020). Transitioning from conventional quality management approaches to digitally enhanced systems is essential to mitigate pervasive issues such as rework and defects, which can constitute 6% to 15% of total construction costs (Lawani et al., 2023), while also bridging the gap toward adopting AI technologies for improved quality assurance. Traditional methods often fail to convert the vast amounts of quality management data into actionable insights, which can be addressed by automated, data-driven systems such as big data. By integrating AI and digital tools, construction projects can achieve more consistent and reliable quality outcomes, prevent costly non-conformities, and meet the industry's evolving demands, paving the way for sustainable advancements in the sector (Sota, 2017).

Study Objectives

The primary objectives of this study is to understand and to quantitatively analyze the performance of a traditional Construction Quality Management (CQM) system by examining key metrics such as the volume, type, and resolution time of quality issues in a large-scale infrastructure project. Also, assess the perceptions and experiences of construction professionals regarding the effectiveness of traditional CQM practices, including management and organizational awareness, and their readiness, especially at the top management, to adopt AI-powered solutions. Additionally, identify specific failure points and bottlenecks in traditional CQM workflows that are exacerbated by project scale and complexity; and to provide a set of actionable, evidence based recommendations for the construction industry to transition towards a more effective, data-driven, and technologically advanced approach to quality management. This will help the construction industry in bridging the gap for leveraging the growing AI-based technologies to enhance project outcomes and foster a culture of proactive quality assurance, ultimately moving towards defect-free project delivery.

Theoretical Literature of the Study

The theoretical foundation of this study is rooted to the established principles of quality management as defined by frameworks such as The Project Management Body of Knowledge (PMBOK) and ISO 9001 (International Organization for Standardization, 2015; Project Management Institute, 2021). These frameworks advocate for systematic approach to quality through quality planning, assurance & control, and continuous improvement. This study is applying these principles to a real-world ongoing infrastructure project in Jeddah, to test their practical limitations. Furthermore, the research draws upon the emerging body of literature surrounding the application of AI in the construction industry. The theoretical model applied is one of a technology-acceptance framework, where the identified shortcomings of the traditional system create a clear need for the adoption of new technologies like AI to overcome inherent human and systemic limitations in processing vast amounts of data and identifying complex patterns. This integration facilitates more predictive and proactive quality management strategies, moving beyond reactive problem solving approach.

Review of Previous studies

The construction industry has long been identified as one of the least digitized sector, a factor that contributes significantly to its well documented struggle with productivity, cost overruns, quality issues, and project delays. Despite the availability of digital technologies, quality management in construction and its adoption to technology has still not received research attention and efforts compared to other industries (Luo et al., 2022). This reliance on manual processes makes the management of large and mega projects unnecessarily complicated. Abioye et. al. (2021) directly link this lack of digital maturity to “poor quality performance”, uninformed decision making and poor performance. It suggests a clear need for advanced technological integration to mitigate these issues within the sector (Datta et al., 2024). Previous studies have consistently identified several key themes where traditional Construction Quality Management practices fail:

- **Misunderstanding and inadequate implementation of Quality Management Systems:** Many construction firms do not fully perceive or implement known QMS like ISO 9001, often due to lack of understanding and training or organizational readiness to adopt it (Aichouni et al., 2014).
- **Inadequacy of tools, Poor data visibility, and converting data to actionable information:** Manual, paper-based, or spreadsheet-driven systems, and segmented data gathering struggle to manage large volumes of data, leading to difficulties in transforming data into usable insights or reports for better decision making (Ji, 2018).

- **Inconsistent process implementation:** Traditional methods often lead to variations in how quality control is applied. These inefficiencies often result in misinterpretations of quality requirements and delayed identification and resolution of defects, further exacerbating project risks and compromising final output quality (Kashif et al., 2022).
- **Reactive rather than proactive quality control:** This approach means that issues are frequently identified and addressed only after they have manifested, rather than being prevented through systematic measures. Which leads to significant negative consequences on project performance (Vishe, 2023).
- **Inefficiency and ineffectiveness in project delivery:** This widespread issue in the construction sector, due insufficient QMS and practices, frequently leads to significant consequences such as rework, extensive delays, and substantial cost overruns (AlMunifi & Almutairi, 2021; Kashif et al., 2022).
- **Poor quality performance, uninformed decision-making, and low productivity:** These are directly linked to the lack of digital maturity and reliance on traditional methods which cannot produce insights for better decision making and for better decision and mitigation of risks (Datta et al., 2024).
- **Delayed and inconsistent communication:** The complexity of large projects, coupled with numerous stakeholders and geographic distribution, creates communication hurdles that makes the exchange of project requirements and expectations harder (Fawzy et al., 2025).
- **Significant cost of quality implications:** Traditional deficiencies in construction quality management result in substantial appraisal, prevention, and internal/external failure costs. These costs are exacerbated by the industry's reliance on manual processes and reactive approaches, leading to inefficiencies and project delivery challenges (Kashif et al., 2022).
- **Lack of digital maturity and reliance on manual processes:** The construction industry is one of the least digitized sectors, with a heavy dependence on manual QA/QC practices (Toyin & Sattineni, 2025).

These failures primarily revolve around inconsistent application of quality protocols, inadequate data capture and analysis, and reactive rather than proactive defect management (Luo et al., 2022). Researchers constantly highlight that construction projects frequently suffer from rework, delays and cost overruns due to deficiencies in quality management processes (Kashif et al., 2022). To this end, the integration of AI in CQM presents a transformative opportunity to enhance precision, effectiveness and efficiency of CQM processes, which can help to move the current CQM practices beyond the limitations of manual ones.

The discussion above highlights the research gap and the need for more empirical, real world and field based evidence which is addressed by this paper. It not only confirms the widely acknowledged challenges but also quantifies their impact in the context of a large-scale infrastructure program. While previous studies have often been broader in scope or based on surveys alone, this paper integrates data from completed and ongoing projects and a survey response from professionals working in the same and similar programs. This combination provides a more holistic and grounded analysis and insights results.

Research Methodology

This study used a mixed-method approach, as guided by the framework outlined in *Designing and Conducting Mixed Methods Research* by Creswell and Plano Clark (2018). The methodology involved two primary components, a qualitative analysis of projects data to examine actual construction quality management outcomes, and a quantitative assessment through a survey capturing stakeholder perceptions regarding current practice and the potential for AI enhancement. This configuration allows for a robust evaluation of both the operational realities and managerial readiness within large scale infrastructure projects.

The first part of the methodology is Qualitative analysis of archival data. A detailed analysis was conducted on the PMO Quality Master Log from infrastructure program in Jeddah. This log included 329 quality field reports, including 246 SORs and 83 NCRs, spanning a six-year period from January 2019 to January 2025. The analysis focused on key metrics such as frequency of different issue types, the time taken to close reports and the distribution of issues across different projects and contractors. Issues were categorized into 4 major parts, Procedural, Materials, Excavation-related, and concrete. The validity of this data is high, as it represents official project records.

The second part involved a survey of construction professionals, a sample of 187 was collected from professionals with experience working on the same program and similar ones in Saudi Arabia. The survey instrument was designed to gather data on their professional background, their experiences with CQM challenges, and their perceptions of AI's potential role in quality management. The reliability of experienced professionals, with over 70% of respondents having more than 10 years of experience. This dual-methodological approach provides a robust framework to not only identify prevailing CQM deficiencies but also to explore the moderating influence of AI on project outcomes

Results

The analysis of PMO logs and survey data revealed recurring quality deviations and extended resolution times for site observations and non-conformities, in large-scale infrastructure projects. Highlighted issues includes largely unfollowed procedures, which contributed as a root cause for other recurring issues. Survey responses further highlighted stakeholders recognition of these challenges and the potential for AI-Driven solutions to enhance the traditional CQM practices.

PMO Log Analysis

The PMO log analysis revealed two dominant patterns for quality non-conformance. First, prolonged resolution times were observed across SORs and NCRs. The analysis shows systematic inefficiencies in reactive quality management. The average closure time for SORs was 91 days (median 40 days), and for NCRs, it was 101 days (median 52 days), with extremes reaching 1,482 days for SOR and 613 days for NCR. These delays were closely linked to failures in following prescribed work procedures, making it hard to solve and close the non-conformance work. Unfollowed work procedures also acted as root cause for the recurrence of many issues across projects, indicating a reactive than proactive CQM practices. The predominance of poor closure responses as shown on Figure (1), with 64% delay for SORs and 72% for NCRs, underscores the inadequacy of traditional CQM practices in managing large-scale infrastructure projects proactively, emphasizing the need for more structured and technology-supported approaches.

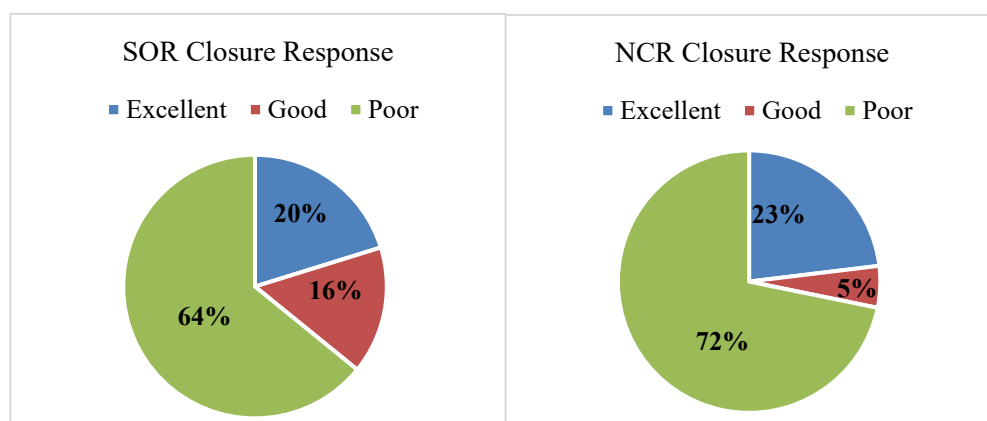


Figure (1) SORs and NCRs Closure response

Second, high frequency issues categories were identified, with core construction activities accounting for the majority of non-conformity. Table (1) below gives a summary of total occurrences of each category and sub-categories. With Materials scoring the highest (154 occurrences), Storage issues (55), and approvals issues (53). Second was Trench related activities (total 148), with further subcategory analysis revealing procedural deviations such as improper layering and compaction (51), lack of dewatering methodology (49). Concrete related issues had the lowest occurrences (84), since it was issued between 2019 and 2021 when cast in situ were allowed, and before changing the supplying of concrete elements to precast, supplied from specialized factories. This shift to precast concrete significantly mitigated on-site quality control challenges associated with concrete pouring and curing to a controlled manufacturing environment, significantly reducing the incidence of concrete pouring issues onsite.

Table (1) Total Occurrences of Quality Issues for each Category

Category	Sub-category	No. of Occurrences	Category Total
Trench	Trench-Irruglar Cut	19	167
	Trench-Backfilling	51	
	Trench-Caves	19	
	Trench-Dewatering	49	
	Trench-Utilities	16	
	Trench-Asphalting	13	
Materials	Materials-Damage	39	153
	Materials-Storage	55	
	Materials-Approval	53	
	Materials-Unavialble	6	
Procedures	Procedures-Unfollowed	48	131
	Procedures-Drawing Approval	28	
	Procedures-Specs.	24	
	Procedures-MOS	31	
Concrete	Concrete-Reinforcement	17	84
	Concrete-Formwork	21	
	Concrete-Water-Stop	3	
	Concrete-PreCasting	4	
	Concrete-After Casting	34	
	Concrete-Coating	5	

The analysis identified 131 instances of procedural non-compliance, highlighting a systemic weakness in following established quality management processes. These were categorized into four main areas: Procedures – Unfollowed (48), Drawing Approval (28), Specifications unfollowed (24), and unfollowed Method of Statement (MOS) (31). Each category contributed to recurring quality deviations; for example, failures to follow approved drawings or MOS frequently resulted in improper installations, while deviations from specifications led to material and workmanship non-conformances. This breakdown emphasizes that procedural lapses are a primary driver of both recurring issues and prolonged resolution times in large-scale infrastructure projects. These findings corroborate earlier research highlighting the construction industry's struggle with a "right first time" culture and the significant impact of unforeseen changes and human behaviors on project delivery (Ford et al., 2023).

Survey Analysis

The survey findings indicate widespread recognition of challenges associated with traditional CQM practices. Among the 187 respondents, the highest reported difficulties were in tracking and closing defects, ensuring compliance with specifications, and addressing gaps in workforce skills and training. Table 2 presents the detailed distribution of responses, including weighted averages. For example, 49.14% of respondents agreed and 13.71% strongly agreed that early identification of quality defects is challenging, resulting in a weighted average of 3.53. Similarly, 47.70% agreed and 24.71% strongly agreed that gaps in workforce skill and training affect quality management, with a weighted average of 3.81. These results align closely with the PMO log analysis, which showed prolonged resolution times and recurring quality issues due to procedural lapses, highlighting that operational bottlenecks are well recognized by professionals and have tangible impacts on project outcomes.

Challenge	Strongly Disagree	Disagree	Neutral / Not Sure	Agree	Strongly Agree	Total Respondents	Weighted Average
Difficulty in identifying quality defects at early stages	2.29%	18.86%	16.00%	49.14%	13.71%	175	3.53
Challenges in managing and tracking defect resolution	2.89%	16.76%	13.29%	54.91%	12.14%	173	3.57
Difficulty ensuring compliance with standards/specifications	5.78%	17.92%	17.92%	41.62%	16.76%	173	3.46
Ineffectiveness in implementing corrective actions	6.90%	25.86%	19.54%	39.08%	8.62%	174	3.17
Lack of structured preventive action mechanisms	4.62%	16.18%	24.28%	42.77%	12.14%	173	3.42
Gaps in workforce skill level and training	4.02%	8.05%	15.52%	47.70%	24.71%	174	3.81
Absence of standardized quality strategies or best practices	5.17%	18.39%	17.24%	43.68%	15.52%	174	3.46

For the effect of CQM practices on construction projects outcomes, cost, time, overall quality and customer satisfaction, most respondents agree that quality management practices help control project costs, reduce rework, and proactively mitigate cost-related risks. Weighted average scores are high (around 4.0), indicating strong confidence in the cost benefits of quality practices. There is broad agreement that robust quality management reduces schedule overruns and that early detection of quality issues helps avoid delays. Scores for schedule-related items are among the highest, reflecting strong positive perceptions. Respondents also believe that quality management improves overall project quality, with high agreement that outputs comply with standards and that post-handover defects are minimal. Customer satisfaction is positively linked to quality management, with most participants agreeing that clients are satisfied and that feedback is used to improve performance. In summary, the data shows that quality management practices are widely seen as beneficial for cost control, schedule adherence, project quality, and customer satisfaction in current projects.

Moreover, the survey revealed a strong appetite for AI and digital technologies to enhance quality management (Table 3). Over 80% of respondents indicated confidence that AI could meaningfully improve CQM outcomes, especially in areas such as automated defect detection, predictive analytics for quality issues, and automated compliance verification. These expectations are directly aligned with challenges frequently detected such as materials storage and approvals, highlighting the limitation of traditional, reactive quality management practices. The survey responses also underscore not only a readiness to embrace technological solutions but also a recognition that AI could proactively address inefficiency and reduce the recurrence of preventable non-conformities, bridging the gap between current operational realities and the potential for data-driven quality improvement and decision making.

Table (3) Survey Responses on Readiness for AI Adoption		
AI Application Area	Number of Respondents	Percentage (%)
Automated defect detection	152	81%
Predictive analytics for quality issues	149	80%
Automated compliance checking	145	78%
AI-assisted reporting & dashboards	130	69%
Resource optimization & planning	125	67%

Conclusion and Discussion of Results

The findings of this study unequivocally indicate that traditional CQM practices are no longer adequate for managing quality in large-scale infrastructure projects. The qualitative analysis of PMO logs highlights systematic inefficiencies that have a direct impact on projects' performance. Prolonged resolution times for site observations and non-conformity reports, SORs & NCRs, were particularly highlighted, with average closure times of 91 days for SORs, and 101 days for NCRs, with medians of 40 and 52 days respectively, and extremes reaching 1,482 and 613 days. These delays were closely associated with procedural lapses, including failures to follow approved work procedures, drawings, specifications and MOS, which acted as a root cause for the recurring of non-conformities. Analysis of issue categories further revealed that fundamental construction activities including materials storage and approvals, trenching activities, and dewatering were accounted for the majority of reported issues. This finding reinforces the notion that adherence to core procedures remain a critical vulnerability in traditional CQM practices. Additionally, these issues raise the need to having more preventive quality system than reactive ones.

The survey data is complementing the operational findings, demonstrating that professionals on the ground are aware of these limitations of current CQM practices. Among 187 respondents, 76% reported difficulties in tracking and closing defects, 74% highlighted challenges in ensuring compliance with specifications, and 70% struggled with implementing corrective actions timely. High recognition of these challenges across the workforce underscores the systematic nature of the problem and aligns with previous studies that have identified the construction industry's overreliance on manual process and low digital capabilities as primary causes of inefficiencies (Luo et al., 2022; Abioye et al., 2021; Datta et al., 2024). Moreover, the survey revealed a strong appetite for AI and digital technologies, with 80% of respondents indicating confidence that AI could significantly enhance quality management outcomes, particularly in automated defect detection, predictive analytics, and compliance verification.

Integrating these quantitative and qualitative findings strengthens the evidence that traditional CQM practices struggle to cope with the scale and complexity of modern infrastructure projects. The combination of delayed responses, recurrent procedural violations, and the limited capacity of existing tools (manual logs, spreadsheets, segmented reporting) not only increases the risk of rework and cost overruns but also undermines structural integrity and safety. These results echo prior research on the inefficiency of conventional CQM systems and further demonstrates the need for a paradigm shift (Aichouni et al., 2014; Kashif et al., 2022; Lawani et al., 2023).

Overall, the study emphasizes that while the foundational principles of quality management (Planning, control, assurance, and continuous improvement), remain valid, their execution through traditional, manual, and reactive method is sufficient for large scale projects. The empirical evidence provided by the PMO logs, coupled with the perceptions captured in the survey, highlights the critical need to adopt technology augmented solutions. Technologies such as AI-driven analytics, automated compliance monitoring, and predictive quality control systems will help in moving the current CQM practices forward. Such transition would not only enhance the effectiveness and efficiency of CQM practices but also provide a scalable framework capable of managing the complexities of modern construction projects. It can lay the foundation and groundwork for further research on AI integration in construction quality management.

Recommendations

Based on the findings of this study, the following recommendations are presented to address the limitations of traditional CQM and guide researchers and the construction industry toward a more effective, data driven, proactive approach:

- **Standardize Quality Processes and Checklists:** the high frequency of having segmented manual tools such as spreadsheets, and the high frequency of basic quality issues highlights the need for greater standardization. The use of enterprise platforms such as ACONEX help to digitize the checklists and standardized workflows, enforcing through digital platforms, can ensure critical quality steps are followed.
- **Promote Training and Upskills:** survey results indicated a need for both AI-related training and reinforcement of fundamentals quality management principles. A skilled workforce is better equipped to adopt new technologies and help to apply quality processes effectively.
- **Move away from disconnected spreadsheets:** there is a need to stop using paper-based logs by implementing centralized, cloud-based quality management platforms. This ensures all stakeholders work with the same real-time data, improving coordination and decision-making.
- **Adopt Integrated Digital Platforms:** the use of platforms such as ACONEX can consolidate data and reports from all project segments and departments, providing a unified view of project quality and simplifying the integration and the use of AI-powered capabilities.

- Invest in AI-Powered Analytics: Transition from reactive to proactive quality management by leveraging AI and machine learning tools. These technologies can analyze historical data to predict potential quality issues, enabling preventive actions and reducing rework.

By embracing these recommendations, the construction industry can move towards a more efficient, proactive, and data-driven approach to quality management, ultimately leading to higher quality projects delivered on time and within budget.

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Midocean University

Ph.D. program

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

(A Case Study of Stormwater Program)

Prepared by
(ISMAIL HASAN R. UJAIMI)

A Dissertation submitted to Doctorate Program
In partial fulfillment of the requirements for the Degree of
Doctor of Philosophy (PhD) In Management

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استكشاف الدور المُعدّل للذكاء الاصطناعي في تأثير ممارسات إدارة
الجودة
على نتائج مشاريع البناء
دراسة حالة من برنامج مياه الأمطار

إعداد

إسماعيل حسن رشاد عجمي

رسالة مقدمة إلى برنامج الدكتوراة
كجزء من متطلبات نيل درجة الدكتوراه في إدارة الأعمال

العام الجامعي 2026م

1447هـ - 1448هـ

هيئة المراجعة والاعتماد العلمي والمناقشة

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مدير برنامج الدكتوراة
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قال رسول الله صلى الله عليه وسلم:

" إِنَّ اللَّهَ تَعَالَى يُحِبُّ إِذَا عَمِلَ أَحَدُكُمْ عَمَلًا أَنْ يُتَّقِنَهُ " رواه البيهقي

إهداء

إلى من كان لهما الفضل بعد الله في كل خطوة من خطوات حياتي،
والديّ الكريمين، حفظهما الله،
اللذين غرسا في نفسي حب العلم والإصرار على طلبه

إلى زوجتي العزيزة،
التي كانت سنداً دائماً ودافعاً للاستمرار في مسيرة البحث والمعرفة

إلى وطني الحبيب المملكة العربية السعودية،
أرض الحرمين الشريفين،
الذي أولى العلم والمعرفة عناية كبيرة،
وسعى إلى تمكين الإنسان وبناء مستقبله

إلى كل معلم أفاد، وكل باحث اجتهد،
وإلى كل من يسعى لنشر العلم والمعرفة وخدمة المجتمع

أهدي هذا العمل المتواضع،
راجياً من الله أن يجعله نافعاً ومفيداً

الشكر والتقدير

الحمد لله أولاً وآخراً، الذي بنعمته تتم الصالحات، والذي وفقني لإتمام هذا العمل وإتمام هذه المرحلة العلمية.

ويسرني أن أتقدم بخالص الشكر وعظيم التقدير إلى الأستاذ ناصر بن إبراهيم المحيميد، الذي كان له دور بارز في نشأة هذا الكيان وتطوره، حيث حمل رؤية طموحة ومبكرة نحو تبني التعليم الإلكتروني والتعليم عن بُعد، وسعى إلى ترسيخ هذا التوجه وتطويره بما يسهم في توسيع فرص التعلم وإتاحة المعرفة للجميع. وقد كان لتلك الرؤية أثرٌ كبير في دعم هذا البرنامج وإتاحة الفرصة لإتمام هذه الدراسة.

كما أتقدم بجزيل الشكر والتقدير إلى جميع أساتذتي الكرام في برنامج الدكتوراه، لما قدموه من علمٍ وتوجيهٍ وإرشادٍ أسهم في إثراء تجربتي العلمية وتطوير معارفي البحثية.

ولا يفوتني أن أعبر عن خالص تقديري لزملائي وزميلاتي في الدفعة، لما ساد بيننا من روح التعاون وتبادل الخبرات والمعرفة، الذي كان له بالغ الأثر في إثراء تجربتنا الأكاديمية طوال فترة الدراسة.

كما أخص أسرتي الكريمة بجزيل الشكر والامتنان على دعمهم المتواصل وصبرهم وتشجيعهم الدائم، والذي كان له الأثر الأكبر في الاستمرار والمضي قدماً حتى إتمام هذه الرسالة.

وفي الختام، أسأل الله أن يجعل هذا العمل خالصاً لوجهه الكريم، وأن ينفع به.

Abstract

The construction industry continues to face persistent challenges in achieving consistent project outcomes related to cost efficiency, schedule adherence, quality performance, and stakeholder satisfaction. Despite the widespread adoption of Construction Quality Management (CQM) practices, many large infrastructure projects still experience quality deviations, rework, and performance inefficiencies. Emerging digital technologies, particularly Artificial Intelligence (AI), present new opportunities to enhance traditional quality management systems by enabling predictive analytics, automated monitoring, and data-driven decision-making. However, empirical evidence regarding how AI influences the effectiveness of CQM practices remains limited. This study therefore investigates the moderating role of artificial intelligence in the relationship between construction quality management practices and project outcomes within complex infrastructure projects.

The study adopts a mixed-methods research design combining quantitative and qualitative approaches to obtain a comprehensive understanding of the phenomenon. The quantitative component employed a structured questionnaire targeting professionals involved in infrastructure projects within the Jeddah Stormwater Program in Saudi Arabia. The survey measured four core dimensions of Construction Quality Management, quality planning, quality assurance, quality control, and quality improvement, alongside project outcome indicators including cost performance, schedule performance, quality performance, and stakeholder satisfaction. Data were analyzed using statistical techniques including reliability testing, correlation analysis, hierarchical regression, and structural equation modeling (SEM) using SPSS and SmartPLS. The qualitative component involved the analysis of project documentation, including non-conformance reports and project management records, to triangulate and contextualize the quantitative findings.

The results demonstrate a statistically significant relationship between Construction Quality Management practices and project outcomes, with CQM explaining a substantial proportion of project performance variance. The findings confirm that effective implementation of quality planning, assurance, control, and improvement contributes positively to achieving successful project outcomes. However, the statistical

analysis indicates that artificial intelligence does not yet exhibit a strong moderating effect within the tested model. Instead, AI technologies currently function primarily as operational enablers that enhance data analysis, monitoring, and decision support rather than structurally transforming quality governance systems.

The study concludes that the construction sector is presently transitioning toward an AI-enhanced quality management paradigm, where digital tools augment existing processes but have not yet fully integrated into governance frameworks. Based on these findings, the research proposes a conceptual direction for future development through the introduction of the Quality Intelligence Model (QIM), which emphasizes the early integration of AI within project quality governance to enable predictive quality management, intelligent risk detection, and data-driven project control. The study contributes to the literature on Construction Quality Management and Quality 4.0 by providing empirical evidence on the interaction between AI technologies and quality management practices within complex infrastructure environments, while offering practical recommendations for improving digital quality governance in large-scale construction projects.

المستخلص

تواجه صناعة التشييد تحديات مستمرة في تحقيق نتائج المشاريع المتعلقة بالكلفة والوقت وجودة التنفيذ ورضا أصحاب المصلحة، وذلك رغم تبني ممارسات إدارة الجودة في المشاريع الإنشائية على نطاق واسع. إذ لا تزال العديد من مشاريع البنية التحتية الكبرى تعاني من عدم تحقيق الجودة وإعادة العمل وضعف الكفاءة في الأداء. ومع التطور السريع للتقنيات الرقمية، برزت تقنيات الذكاء الاصطناعي كأحد الأدوات الواعدة التي يمكن أن تعزز أنظمة إدارة الجودة التقليدية من خلال تمكين التحليل التنبؤي ومراقبة العمليات بشكل آلي ودعم اتخاذ القرار المبني على البيانات. ومع ذلك، لا تزال الأدلة العلمية حول كيفية تأثير الذكاء الاصطناعي في تعزيز فعالية ممارسات إدارة الجودة في مشاريع التشييد محدودة. لذلك تهدف هذه الدراسة إلى استكشاف الدور المعدل للذكاء الاصطناعي في العلاقة بين ممارسات إدارة الجودة في مشاريع التشييد ونتائج المشاريع في بيئة مشاريع البنية التحتية المعقدة.

اعتمدت الدراسة منهجية البحث المختلط التي تجمع بين الأساليب الكمية والنوعية للحصول على فهم أكثر شمولية لموضوع الدراسة. في الجانب الكمي تم استخدام استبانة موجهة إلى المختصين العاملين في مشاريع البنية التحتية ضمن برنامج تصريف مياه الأمطار بمدينة جدة في المملكة العربية السعودية. وقد تضمنت الاستبانة أربعة أبعاد رئيسية لإدارة الجودة في مشاريع التشييد وهي: تخطيط الجودة، وضمان الجودة، وضبط الجودة، والتحسين المستمر للجودة، بالإضافة إلى مؤشرات نتائج المشاريع التي تشمل أداء التكلفة وأداء الجدول الزمني وجودة التنفيذ ورضا أصحاب المصلحة. وتم تحليل البيانات باستخدام عدد من الأساليب الإحصائية مثل اختبار الموثوقية ومعاملات الارتباط والانحدار الهرمي ونمذجة المعادلات الهيكلية باستخدام برنامج التحليل الإحصائي SPSS وكذلك برنامج SmartPLS. كما تم دعم النتائج الكمية بتحليل نوعي لعدد من الوثائق والبيانات المتعلقة بالمشاريع مثل تقارير عدم المطابقة والسجلات الإدارية للمشاريع مثل محاضر الاجتماعات بهدف تعزيز موثوقية النتائج وتفسيرها.

أظهرت نتائج الدراسة وجود علاقة ذات دلالة إحصائية بين ممارسات إدارة الجودة في مشاريع التشييد ونتائج المشاريع، حيث تفسر ممارسات إدارة الجودة نسبة معتبرة من التباين في أداء المشاريع. كما أكدت النتائج أن التطبيق الفعال لأبعاد إدارة الجودة الأربعة يسهم بشكل إيجابي في تحسين نتائج المشاريع. إلا أن نتائج التحليل الإحصائي أوضحت أن الذكاء الاصطناعي لا يظهر

حالياً تأثيراً تعديلياً قوياً في النموذج الإحصائي المستخدم، بل يعمل في المرحلة الحالية كعامل داعم يعزز عمليات تحليل البيانات والمراقبة واتخاذ القرار دون أحداث تحولاً جذرياً في أنظمة الجودة.

وتخلص الدراسة إلى أن قطاع التشييد يمر حالياً بمرحلة انتقالية نحو نماذج إدارة جودة مدعومة بالذكاء الاصطناعي، حيث تسهم الأدوات الرقمية في تعزيز كفاءة العمليات القائمة دون أن يتم دمجها بشكل كامل ضمن أطر الحوكمة المؤسسية للمشاريع. وبناءً على ذلك تقترح الدراسة توجهاً بحثياً مستقبلياً يتمثل في تطوير واختبار نموذج مفاهيمي لإدارة الجودة الذكية (Quality Intelligence Model - QIM) يركز على دمج تقنيات الذكاء الاصطناعي في مراحل مبكرة من دورة حياة المشروع بما يدعم التنبؤ بالمخاطر وتحليل بيانات الجودة واتخاذ القرارات المبنية على البيانات. وتسهم هذه الدراسة في إثراء الأدبيات العلمية في مجال إدارة الجودة في مشاريع التشييد وجودة 4.0، كما تقدم مجموعة من التوصيات العملية لتحسين حوكمة الجودة الرقمية في مشاريع البنية التحتية الكبرى.

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List of Abbreviation

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

CHAPTER ONE

LITERATURE REVIEW

1.1 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.

1.2 Keywords

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

1.3 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 in 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 for 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.

1.4 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.

Moreover, 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 workload 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.

1.5 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.

1.6 Significance of Study

1.6.1 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.

1.6.2 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.

1.6.3 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.

1.7 Research Methodology

This study employs a mixed-methods research approach, combining in-depth qualitative case study 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.

1.7.1 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 100 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 quality related 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.

1.8 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.

1.9 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 from practical experience in the field 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 occurrence.

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 (Feng & 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.

1.9.1 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).

1.9.2 Quality Assurance (QA)

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

1.9.3 Quality Control (QC)

On the other hand, QC 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 and 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 standards 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.

1.9.4 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.

1.10 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). Also, involving multiple stakeholders, regulatory requirements, and high-risk activities. Therefore, 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.

1.11 Artificial Intelligence (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). Beyond these established enterprise platforms, emerging AI systems such as Anthropic's Claude, Agentic AI, and Manus AI increasingly integrate ML and NLP capabilities within unified analytical environments. It helps users and organizations to enable analysis of large volume of project documents and operational data to generate actionable insights and fast track repetitive works.

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. Therefore, when 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).

In 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.

1.12 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 projects. AI-driven tools, such as predictive analytics, 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 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 CQM 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 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, through failure detection, and recommending preventive measures based on pattern recognition from historical data.

1.12.1 Research Questions

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

1.12.2 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 within construction and infrastructure projects.

- Hypothesis (H3a): Financial constraints, such as implementation and operational costs, significantly limit the adoption of AI technologies in CQM practices.

- Hypothesis (H3b): Organizational barriers, including resistance to change & lack of skilled personnel, significantly impact the 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 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 Figure (01) 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).

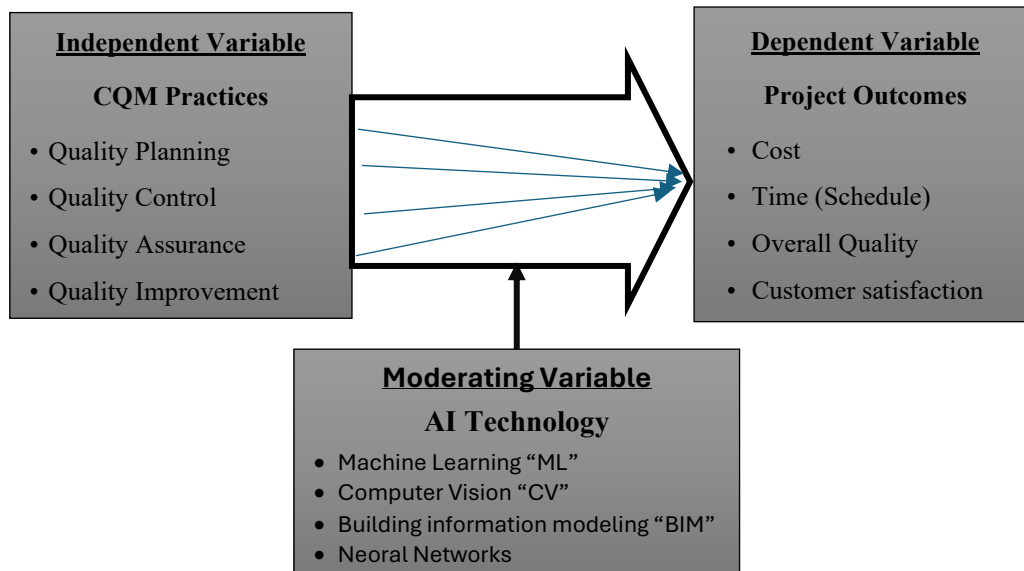


Figure 01 - The diagram represents the variables and their relationships
Source: prepared by the researcher

1.13 Literature Review

1.13.1 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).

1.13.2 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.

1.13.3 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.

1.13.4 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.

1.13.5 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 issue the projects for bidding, JSWP can enhance efficiency, reduce waste, and deliver high-quality outcomes that meet or exceed client expectations.

1.14 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.

1.14.1 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.

1.14.2 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 cut 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.

1.14.3 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.

1.14.4 Challenges for Adopting AI in CQM

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).

1.14.4a 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 & 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.

1.14.4b 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).

1.14.4c 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).

1.14.4d 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.

1.14.4e 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).

1.14.4f 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 AI 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.

1.15 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 conclude 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.

1.15.1 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.

1.15.2 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.

1.15.3 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.

1.15.4 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 (Table 1-1) 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 CQM practices, particularly in large and complex projects, highlighting 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.

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 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.

Table (1-1) Literature Review Summary Table

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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.

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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 ang customer's 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.

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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.

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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				
No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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
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.

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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					
No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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.

No	Title	Author	Year	Literature Summary	Researcher Comments and relevance to JSWP
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.
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.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Overview

Construction Quality Management has emerged as a vital and indispensable factor in determining the success and overall performance of construction projects. CQM is a critical component that significantly contributes to achieving project goals, meeting clients' requirements, and satisfying their expectations. It encompasses a range of processes and procedures that ensure construction projects are delivered to the specified standards and quality levels, ultimately leading to enhanced customer satisfaction and the organization's ability to differentiate itself from competitors in the highly competitive construction industry. As Zhang et al. (2014) explained, organizations are often driven to implement quality management systems either by a rational motivation, seeking to improve internal performance and project outcomes, or by a social motivation, aiming to conform to external expectations and gain legitimacy. Understanding these underlying drivers is essential for evaluating the effectiveness of CQM practices in achieving tangible project success.

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

Understanding the challenges of implementing CQM practices in construction and infrastructure projects, and how these practices impact project outcomes, lays the foundation for incorporating emerging technologies like artificial intelligence to optimize and enhance quality management effectiveness in the construction industry (Hamdan, 2024). AI tools and techniques, such as automating quality processes, identifying and predicting quality issues, can help address the complexities of implementing effective CQM practices. AI-driven solutions can automate and streamline quality control, enable real-time monitoring and data analysis, and provide predictive insights to proactively mitigate quality-related issues. By leveraging AI, construction firms can improve the efficiency and effectiveness of their quality management practices, leading to better project outcomes in terms of cost, schedule, quality, and customer satisfaction (Regona et al., 2023).

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

2.2 Theoretical Foundations of Construction Quality Management

It is crucial to understand the theoretical foundations and principles of construction quality for developing a comprehensive approach to quality management in construction. CQM is rooted in the theoretical principles and frameworks established by quality management pioneers such as W. Edwards Deming, Joseph Juran, Crosby, and Armand Feigenbaum. Deming's philosophy emphasizes process control, statistical quality management, and the Plan-Do-Check-Act (PDCA) cycle, which has become a fundamental aspect of international quality standards like ISO 9001 (Neyestani, 2016).

Juran's Quality Trilogy, quality planning, control, and improvement, has been instrumental in structuring quality processes in construction projects, ensuring that project outcomes align with client expectations and regulatory standards (Juran & Joseph, 2012). Meanwhile, Crosby's "Zero Defects" concept underscores the importance of a defect-prevention mindset, reducing rework and improving cost efficiency in large-scale projects (Crosby, 1980). These foundational concepts provide a strong theoretical basis for understanding the key elements and best practices of quality management, which have been adapted and applied to the unique context of the construction industry.

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

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

Recognizing the inherent complexities and challenges faced by construction projects, the integration of well-established quality management theories, such as those of Deming, Juran, and Crosby, provide a solid framework for effectively implementing CQM practices and addressing the specific quality-related issues that arise in the construction domain. As evidenced by empirical studies within the Saudi construction industry, however, the successful application of these principles requires not only technical knowledge but also organizational commitment, capacity building, and context-sensitive adaptation. By grounding CQM in well-established quality management theories, construction firms can develop a more robust and systematic approach to enhance quality performance, reduce rework, and consistently meet client and stakeholder expectations, thereby ensuring the successful delivery of construction projects that meet or exceed the specified standards, requirements, and customer expectations.

2.3 Quality Management Frameworks

2.3.1 The ISO 9000 series

The ISO 9000 series is a set of internationally recognized standards developed by the International Organization for Standardization (ISO) to establish QMS across industries, including construction. The most widely implemented standard in this series is ISO 9001, which provides a framework for organizations to ensure consistent quality, process efficiency, and customer satisfaction. These standards emphasize a process-driven approach to quality management, focusing on continuous improvement, risk-based thinking, and compliance with regulatory requirements. In construction projects, ISO 9001 certification is often required by clients and regulatory bodies to demonstrate an organization's commitment to quality assurance and compliance with industry best practices (Neyestani, 2016). ISO 9001 (2015) standard outlines seven key quality management principles that are critical in the construction industry:

1. Customer Focus: Meeting & exceeding client expectations in project execution.
2. Leadership: Ensuring quality objectives align with the organization's vision.
3. Engagement of People: Empowering employees at all levels to contribute towards quality implementation.
4. Process Approach: Managing construction activities through well-defined processes and procedures.

5. Continuous Improvement: Continually enhancing construction practices and methodologies.
6. Evidence-Based Decision Making: Using data and audits to drive quality improvements.
7. Relationship Management: Strengthening collaboration with suppliers, subcontractors, and stakeholders.

Implementing ISO 9001 in construction projects requires several important steps, including establishing a documented quality management system, conducting internal and external audits, implementing corrective actions, and continuously monitoring performance metrics. Many construction firms adopt ISO 9001-certified quality systems to streamline document control, material inspections, and compliance procedures, thereby reducing rework costs, project delays, and contract disputes. For large-scale infrastructure projects, such as stormwater networks or highway construction, ISO 9001 provides a standardized framework for managing quality across multiple contractors, subcontractors, and suppliers, ensuring consistency and reliability.

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

Another study on Malaysian construction projects conducted by Mukhtar et. al. (2010) revealed that ISO 9001-certified contractors experienced fewer non-conformance reports (NCRs), lower material wastage, and reduced rework costs, leading to better

project performance and financial savings. The research emphasized that one of the core aspects of ISO 9001 is its focus on performance measurement and continuous improvement, which is particularly relevant for large-scale infrastructure projects. The quality cost approach, which includes prevention, appraisal, and failure costs, was identified as a crucial tool for assessing and improving construction quality performance. However, the study also noted that knowledge gaps among project teams often limit the full potential of ISO 9001, highlighting the need for better training and awareness programs to enhance its effectiveness.

Implementing ISO 9001 Quality Management and ISO 14001 Environmental Management have significantly contributed to the operational success of DB Construction, leading to a 34% annual growth. According to BSI (2011), the integration of these management systems helped the company enhance process efficiency, improve client satisfaction, and strengthen compliance with regulatory requirements. Adopting structured quality management practices by DB Construction helped the company to reduce inefficiencies, streamline documentation, and improve overall project performance, demonstrating the value of internationally recognized quality standards in the construction industry.

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

However, contractors often implement QMS either to align with strategic project goals or to meet regulatory, industry, or project requirements. Zhang et al. (2014) distinguished between the rational perspective, where quality systems are strategically adopted to improve performance, and the social perspective, where they view ISO 9001 as a bureaucratic formality, focusing on passing audits rather than improving quality on-site, which is the case for some contractors in JSWP. In such cases, Quality Manuals are generic, developed only for certification or approval purposes, leading to inconsistent quality control, task delays, and frequent revisions.

Another study from Jordan's construction industry revealed that many ISO-certified firms had employees unaware of the standard's actual significance, reflecting poor implementation and weak integration into daily activities. This reactive approach results in higher defect rates, increased rework costs, and misalignment with quality objectives, ultimately delaying project progress and increasing contractual disputes (Hiyassat, 2000). Such disparities in ISO 9001 adoption are evident within JSWP, which highlights that the true value of a QMS lies in its meaningful implementation, not just its certification.

2.3.2 Total Quality Management (TQM)

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

Several major construction firms have successfully implemented TQM to enhance project outcomes. For example, Bechtel Corporation, a globally recognized engineering and construction company, adopted TQM methodologies and Six Sigma principles to improve processes, reduce construction defects, and minimize the cost of defects and rework. By integrating structured quality control procedures into daily site operations, Bechtel's quality improvement initiatives resulted in \$200 million in savings, following

an initial investment of \$30 million in a defect prevention and process optimization program (Oguz et al., 2012). This case highlights how TQM-driven quality management strategies can lead to significant cost reductions and improved project efficiency in large-scale construction projects.

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

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

While TQM is widely recognized for its benefits in construction, it is not formally implemented in JSWP, as ISO 9001 is followed as its quality management framework. However, the core principles of TQM, continuous improvement, defect prevention, and

process optimization, are inherently embedded within ISO 9001 requirements. Contractors working under JSWP are expected to apply ISO 9001-driven quality management processes, such as structured ITP, MOS, and Material Inspection Requests to maintain compliance and ensure consistency across all projects. The effectiveness of ISO 9001 still depends on how well contractors integrate quality practices into their daily operations rather than treating compliance as a procedural obligation.

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

2.4 The Quality Gurus

2.4.1 Juran's Quality Trilogy in Construction

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

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

or exceed customer expectations, and deliver high-quality infrastructure that stands the test of time.

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

Although JSWP primarily adopts the ISO 9001 quality management framework as a contractual requirement, the core elements of Juran's Quality Trilogy are inherently aligned with the structured approach of ISO 9001. Contractors working under JSWP must engage in comprehensive quality planning through detailed manuals, quality control via Inspection and Test Plans and rigorous inspections, and quality improvement through continuous audits and corrective actions. Effective integration of these complementary principles through ISO 9001, JSWP contractors can foster a proactive quality management mindset, and rather than merely reactive compliance when ISO is only a formality that needs to be done. This approach can help reduce defects, optimize processes, and ultimately improve overall project outcomes.

2.4.2 Deming's PDCA Cycle in Construction

Deming's Plan-Do-Check-Act (PDCA) Cycle is a widely used continuous improvement model that emphasizes an iterative approach to quality management. Initially developed by Dr. W. Edwards Deming, the PDCA cycle ensures that quality is managed proactively rather than reactively, making it particularly valuable in construction projects where deviations from standards can lead to significant cost overruns, delays, safety risks, and reduced customer satisfaction. The cycle consists of four key stages as shown in Figure (02) below.

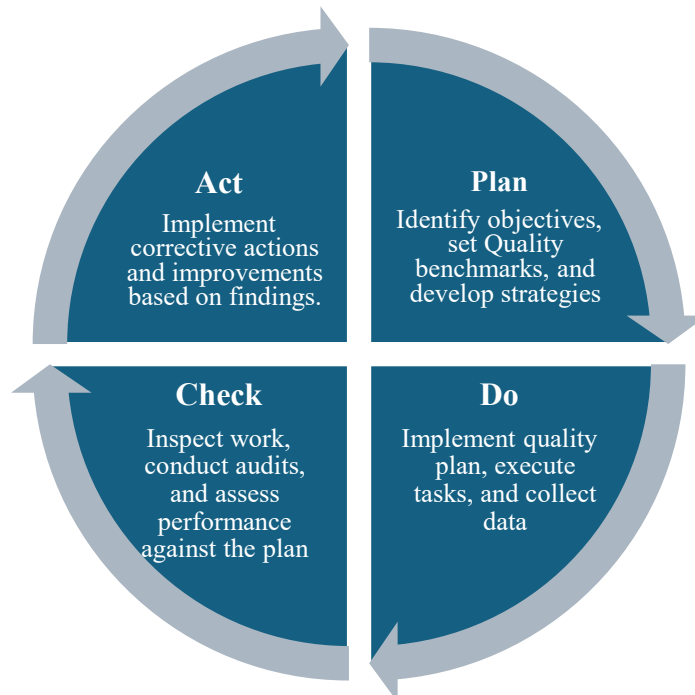


Figure 02: Deming Cycle PDCA
Source: Adapted form Deming (1986)

In Construction, the PDCA cycle is widely applied in construction to ensure proactive quality management, prevent defects, and drive continuous improvement. In the Cross-rail Project (London's Elizabeth Line), the Plan phase was used extensively to define quality benchmarks, conduct risk assessments, and develop quality control strategies, preventing material failures and structural weaknesses before construction began (Project and Program Management, 2023). Check phase played a crucial role in the Hong Kong-Zhuhai-Macao Bridge project, where frequent inspections and real-time monitoring were used to detect early signs of structural stress and ensure compliance with engineering standards, reducing post-construction defects (Zhu et al., 2018). The act phase was used in the Riyadh Metro project, where lessons from early construction phases led to better material selection, workflow efficiency, and safety improvements, minimizing rework and enhancing overall project quality (Abazid, 2017). These examples demonstrate how the PDCA cycle systematically integrates planning, monitoring, and corrective actions to improve project outcomes, reduce defects, and optimize construction processes.

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

2.4.3 Crosby's "Zero Defects" Philosophy in Construction

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

2.4.4 Application in Construction

Crosby's "Zero Defects" philosophy has been successfully applied in various high-profile infrastructure projects, presenting its effectiveness in enhancing quality control and reducing rework. The implementation of strict quality planning, supplier compliance audits, and defect-prevention strategies has helped minimize construction errors and material defects, ensuring that the work meets stringent regulatory and safety standards (Salvi & Kerkar, 2020). This approach, which focuses on doing things right the first time, has been instrumental in improving the long-term performance of construction projects by eliminating material inconsistencies and structural defects.

While the ISO 9001 framework is the primary quality management system in JSWP, Crosby's principles are already embedded in the program's quality approach. Contractors are required to establish comprehensive Quality Manuals, ITPs, and MOSs to ensure quality is controlled at every stage of construction. The contractors who

adhere to JSWP's quality standards, implement supplier audits, inspections, and defect-prevention strategies, are aligning with Crosby's "Zero Defects" philosophy. However, when no planning is in place, Crosby's zero-defect approach may not be effective, which highlights the importance of integrating both the PDCA cycle and Crosby's principles into the quality management system to drive continuous improvement and eliminate defects throughout the construction lifecycle (Hwang & Yang, 2014) (Alinizzi et al., 2020).

2.4.5 Conclusion and Proposed Solution

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

2.5 The Pyramid of Quality

The author developed the pyramid of quality integration to illustrate the evolution of quality thought and its structured application within the construction industry. Figure (03) illustrates the layered integration of quality management thinking into construction practices, showing how foundational theories have evolved into structured systems that drive modern project outcomes. At its foundation are the contributions of quality pioneers, Deming, Juran, and Crosby, who introduced key principles such as continuous improvement, process focus, and defect prevention. These theoretical contributions informed the rise of TQM in the 1980s, emphasizing organizational culture, leadership, and system-wide quality responsibility. Subsequently, the development of the ISO 9001 standard translated these principles into a formalized quality management framework, emphasizing process control, documentation, and continuous auditing.

Within the construction sector, these standards were further operationalized through Construction Quality Management (CQM) practices, including Quality Management Systems, Inspection and Test Plans, Non-Conformance, and on-site inspections. At the top of the pyramid lie the intended results of these layered practices: project outcomes in terms of cost, time, quality, and customer satisfaction.

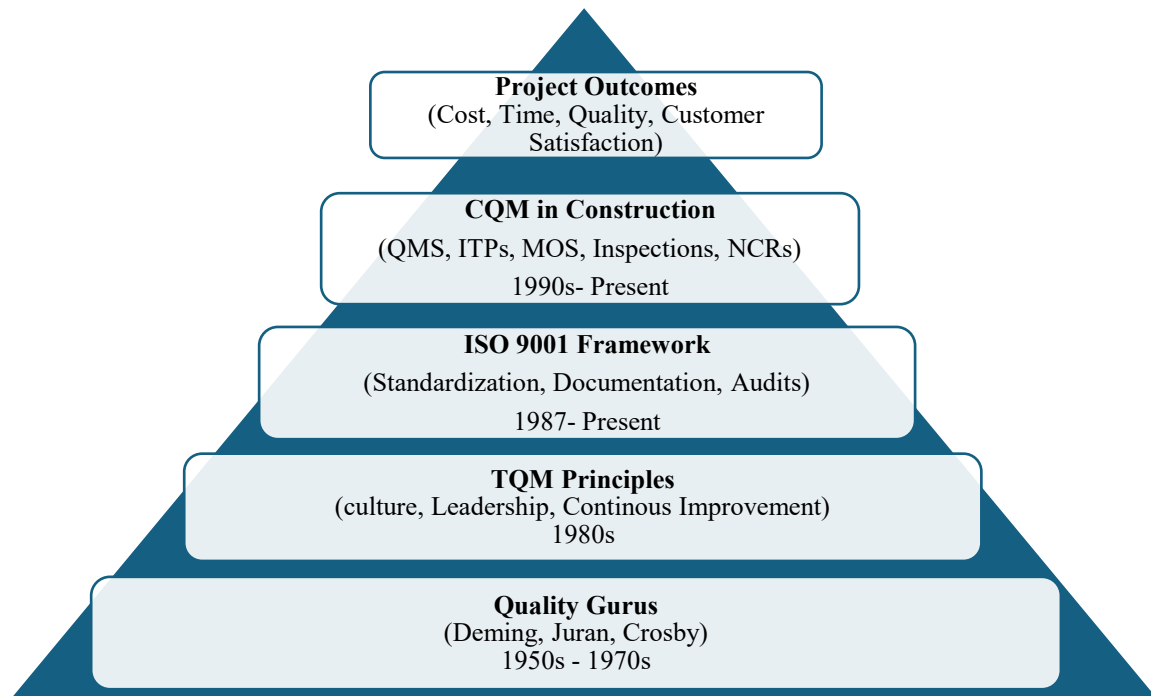


Figure 03: Pyramid of Quality Integration into Construction
Source: Developed by the Author

2.5.1 How ISO 9001 Acts as Integrative Framework

Elements of the discussed quality management theories and models are inherently implemented within JSWP as the program officially adheres to ISO 9001 as its primary quality management system, its implementation naturally integrates fundamental principles from the quality theories. Figure (04) illustrates how the foundational principles and concepts introduced by quality pioneers shaped the development of structured frameworks like TQM and ISO 9001, forming the theoretical backbone of modern quality systems.

From Deming, ISO 9001 inherits the PDCA cycle, process orientation, and emphasis on continuous improvement. While Juran quality trilogy incorporates a structured approach to quality planning, control and improvements, Crosby, reflects the preventive approach over proactive inspections. ISO formalizes TQM's broader

concepts of customer satisfaction, employee & management involvement, and system-wide quality responsibility into documented procedures, measurable objectives, and audit processes.

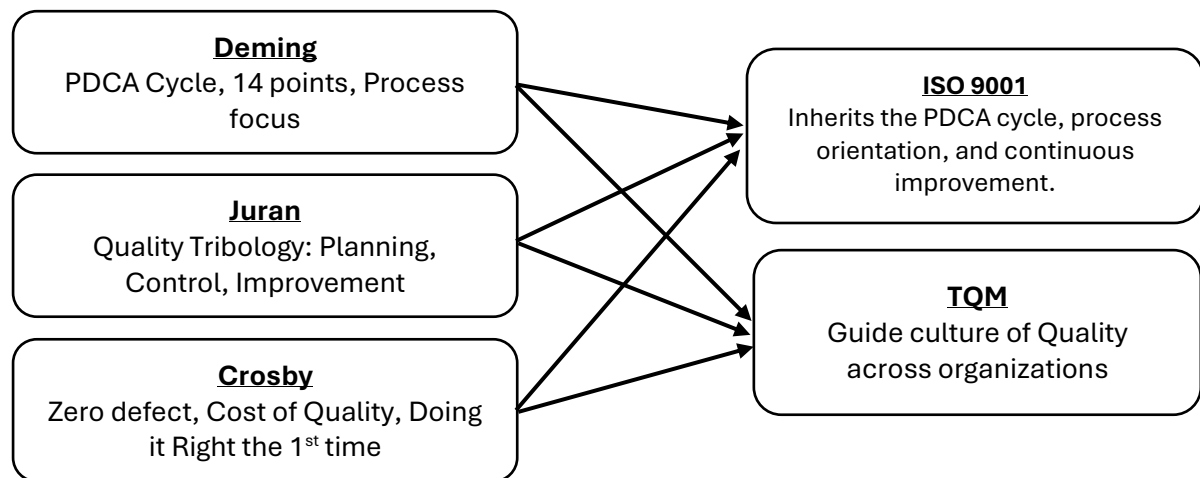


Figure 04: Contributions Of Quality Gurus to Modern Management Frameworks
Source: Developed by the Author

Building on the previous discussion of Figure (04), the overlapping principles of Deming, Juran, and Crosby highlight a shared foundation that underpins modern quality management systems. The Venn diagram on Figure (05) below shows how Both Deming and Juran advocate for continuous improvement, while Crosby and Deming stress defect prevention over post-inspection correction. Juran and Crosby align on the need for structured planning and clear accountability in quality implementation. These overlapping principles not only reinforce the theoretical consistency behind modern frameworks like ISO 9001 and TQM but also justify their integration into Construction Quality Management (CQM) systems used in complex infrastructure projects such as the Jeddah Stormwater Program (JSWP). The interaction of All three emphasizes customer satisfaction, measurable performance, and organizational commitment to quality which are the core values of modern quality management frameworks

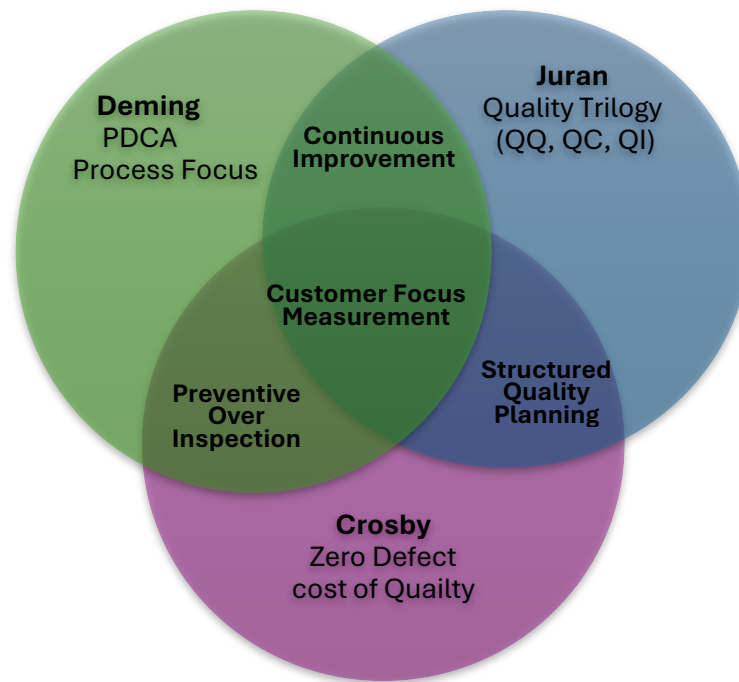


Figure 05: Overlapping Principles of Deming, Juran and Crosby
Source: Developed by the Author

2.5.2 Proposed Solution

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

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

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

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

2.6 Construction Quality Management (CQM)

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

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

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

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

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

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

2.6.1 Construction Quality Management Dimensions

Establishing and implementing an effective Construction Quality Management system necessitates a comprehensive understanding of the key components and fundamental principles that underpin successful construction quality management practices. Building into Juran's Trilogy Construction Quality Management will be divided into four critical dimensions that ensure project success: Quality Planning, Quality Control, Quality Assurance, and Quality Improvement. Each of these dimensions plays a vital role in maintaining compliance with standards, minimizing defects, improving efficiency, and enhancing project outcomes (cost, schedule, quality, and customer satisfaction). In large infrastructure projects, these dimensions contribute to the effectiveness of the quality management system, ensuring that construction activities adhere to regulatory, contractual, and performance requirements.

2.6.1a Quality Planning

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

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

Another component of Quality Planning is identifying potential risks and developing mitigation strategies. This includes conducting risk assessments to detect quality failures, material inconsistencies, and execution errors before they escalate. For instance, during the Palm Jumeirah project in Dubai, early identification of soil

settlement risks led to the use of enhanced compaction techniques and real-time monitoring, ensuring the stability of the artificial islands (Higgins, 2013).

Another vital part of Quality Planning is developing ITPs and MOSs to ensure that construction activities are executed correctly as per requirements. These documents outline inspection frequency, acceptance criteria, and corrective measures, serving as essential tools for maintaining compliance with quality standards. A good example is the Hong Kong-Zhuhai-Macao Bridge project, where rigorous concrete durability and steel reinforcement testing protocols were implemented, preventing premature material degradation (Zhu et al., 2018). Additionally, proper documentation and compliance management are integral to Quality Planning. Maintaining traceable records of quality inspections, material certifications, and work approvals is crucial for regulatory compliance, particularly in ISO 9001-certified projects.

2.6.1b Quality Control

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

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

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

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

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

In conclusion, Quality Control is an essential dimension of CQM that ensures compliance with project specifications, reduces defects, and enhances overall project reliability. In JSWP and other large-scale infrastructure projects, well-structured inspection and testing procedures, combined with effective defect management strategies, contribute to cost reduction, schedule efficiency, and long-term performance of constructed assets. However, the effectiveness of Quality Control depends on how

consistently contractors implement and adhere to these processes, reinforcing the need for strict compliance with ISO 9001 and project-specific quality requirements.

2.6.1c Quality Assurance

Quality Assurance (QA) in construction is a proactive approach that focuses on preventing quality issues before they occur, in contrast to the reactive nature of Quality Control. QA is a preventive, process-oriented approach that ensures quality is built into every phase of the project lifecycle. Unlike QC, which focuses on detecting and correcting defects, QA emphasizes establishing standardized procedures, best practices, and compliance frameworks to prevent defects from occurring in the first place. QA ensures that contractors adhere to project specifications, industry regulations, and contractual requirements, ultimately improving cost efficiency, schedule adherence, and long-term durability (Juran & Joseph, 2012).

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

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

However, with a structured quality assurance framework, projects saw significant improvements in material handling, supplier compliance, and adherence to quality standards. This proactive approach reduces the risk of structural defects, enhances

construction durability, and ensures that materials meet regulatory and project-specific requirements.

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

2.6.1d Quality Improvement

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

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

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

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

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

2.7 Construction Quality Management, Project Outcomes, and AI

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

2.7.1 Cost

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

2.7.2 Schedule (Time)

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

2.7.3 Quality

The degree to which the construction project meets or exceeds the specified design requirements, regulatory standards, and durability expectations for the built infrastructure. This encompasses compliance with design drawings, construction codes and guidelines, as well as the long-term performance and reliability of the completed facility. Effective CQM practices aim to ensure the final product achieves desired level

of quality, functionality, and service life in accordance with stakeholder requirements while exceeding their expectation (Teshome & Gobana, 2018).

2.7.4 Customer Satisfaction

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

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

2.7.5 Impact of CQM on Project Cost

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

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

ISO 9001-based QMS experienced fewer defects, reduced rework, and lower project costs, reinforcing the necessity of a structured quality framework in construction projects (Neyestani, 2016).

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

2.7.6 Impact of CQM on Project Schedule

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

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

promptly implemented before the material is used, to avoid significant schedule disruptions.

2.7.7 Impact of CQM on Project Quality

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

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

These studies align with the needs of JSWP, as quality can be achieved through strict compliance with QMS, especially ISO 9001 standards. The implementation of CQM practices, such as compliance with industry standards, product certifications, and regular third-party inspections, helps ensure the quality and durability of critical infrastructure components, such as water pipes, precast manholes, and marine outfalls. Contractors that prioritize quality management ensure that their structures withstand environmental conditions, minimize maintenance costs, and function efficiently for decades, and as a result contributing positively to sustainability.

2.7.8 Impact of CQM on Customer Satisfaction

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

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

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

2.7.9 AI as an enhancer of CQM

Advancements in digital technologies, particularly Artificial Intelligence (AI), are transforming traditional construction management practices. In the realm of CQM, AI has emerged not as a substitute, but as a powerful enhancer that fortifies each core quality function. By integrating predictive analytics, real-time data processing, and intelligent automation into established quality systems, AI enables construction teams to shift from reactive issue handling to proactive quality assurance. This transformation is especially crucial in large-scale infrastructure projects, where complexity and fragmentation often challenge traditional quality control mechanisms. Table (2-1) below provides a summary of how AI technologies can enhance the four primary dimensions of CQM, by enhancing accuracy, efficacy, and decision-making capabilities across each function.

Table 2-1: AI Technology enhancement for current CQM practices

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

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

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

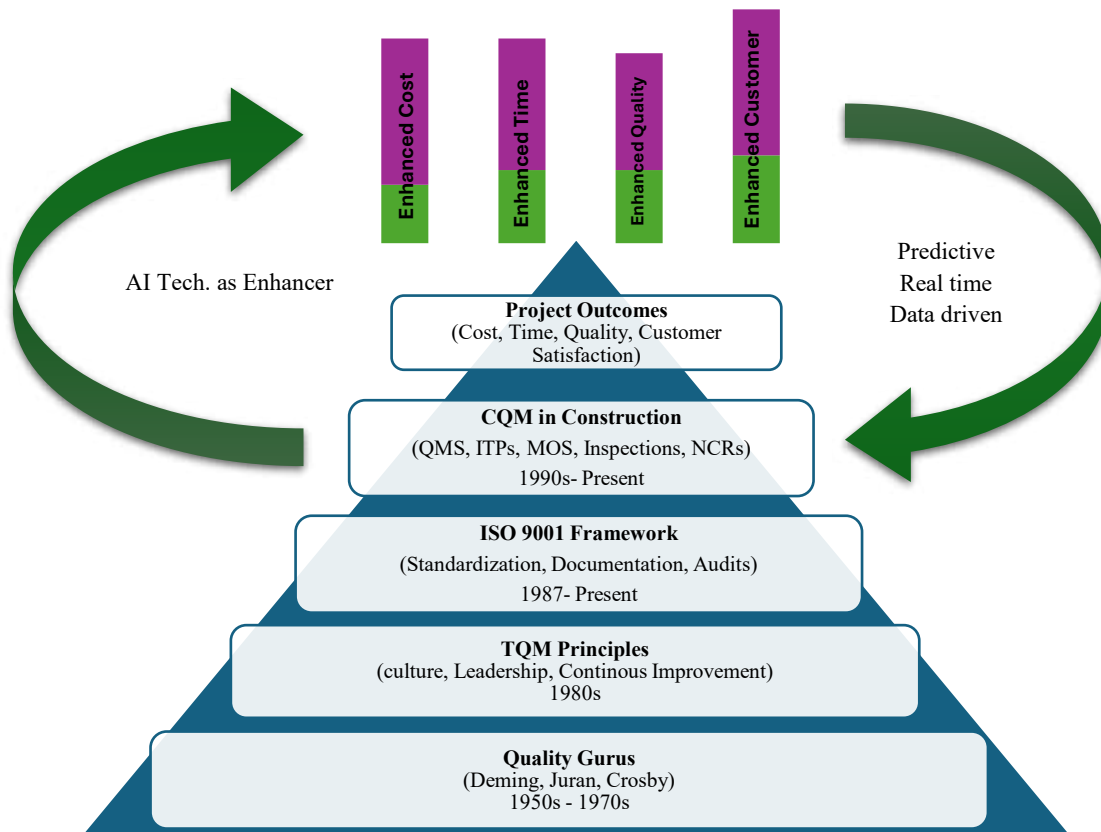


Figure 06: The Pyramid of Quality with integrated AI technology as an enhancer
Source: Prepared by the author

2.8 Research Gaps

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

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

Furthermore, extensive research has been conducted on CQM and its impact on project outcomes. Several gaps remain, particularly in the context of large-scale infrastructure projects like JSWP and the adoption of advanced quality management technologies.

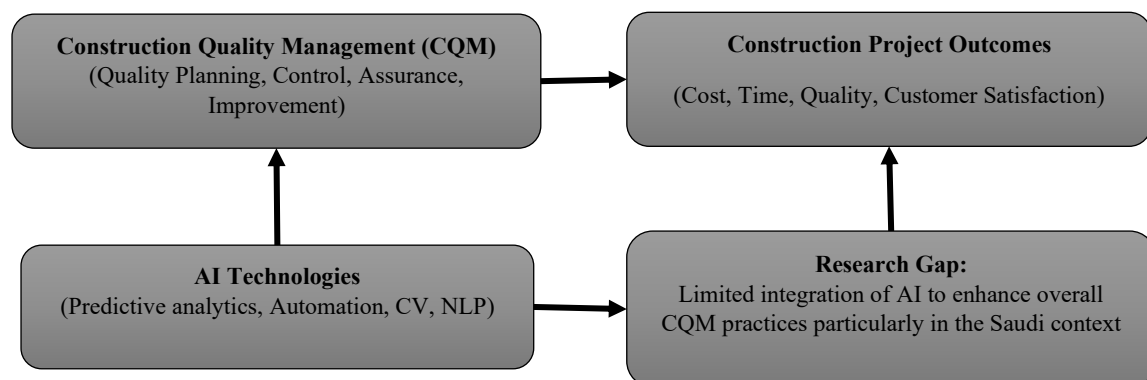


Figure 07: Gap in Literature – The Moderating Role of AI on the Relationship Between CQM practices and Project Outcomes.

Source: Prepared by the author

The key research gaps identified from literature include as illustrated on Figure (07):

- **Limited Studies on CQM in Large-Scale Infrastructure Projects in Saudi Arabia:** While the existing literature provides a general understanding of CQM and its implications, there is a lack of research specifically focused on the challenges and best practices of implementing CQM in large-scale infrastructure projects within the Saudi Arabian context. Existing studies on CQM focused on residential, commercial, or small-scale construction projects, with limited research specifically addressing the challenges and best practices of CQM in large-scale infrastructure projects, particularly in the Saudi Arabian context. There is a lack of empirical data on how ISO 9001-based QMS frameworks perform in programs like JSWP and their effectiveness in mitigating quality risks, cost overruns, and schedule delays.
- **The Need for a Deeper Understanding of CQM's Direct Impact on Project Outcomes:** While studies confirm that quality management improves project performance, there is limited quantitative research on the degree of impact each dimension of CQM on cost, schedule, quality, and customer satisfaction. However, as the complexity and scale of projects increase, such as in JSWP, more in-depth analysis is needed to understand the relative importance and interrelationships between various CQM practices and their direct impact on project outcomes.
- **Challenges in Implementing ISO 9001 in Multi-Contractor Infrastructure Projects:** The literature highlights the challenges faced by construction firms in effectively implementing ISO 9001-based quality management systems, particularly in large, complex projects with multiple contractors and subcontractors. The lack of a unified, collaborative approach to quality management across the supply chain often leads to inefficiencies, inconsistencies, and quality issues.
- **Further research is needed to identify best practices and strategies for implementing robust CQM frameworks in multi-stakeholder infrastructure projects, especially in the context of the Saudi Arabian construction industry.** Although project requirements at JSWP strictly adopt ISO 9001, more investigation is needed to evaluate how ISO 9001 compliance is interpreted and applied differently by contractors and whether it is truly integrated into their daily quality processes or treated as a procedural requirement.

- **The Role of Emerging Technologies in Enhancing CQM Practices:** The existing literature often emphasizes the general advantages of AI in construction, such as its impact on a specific project outcome or its application to specific quality management issues. Studies acknowledge the potential of individual technologies like AI, BIM, and IoT to address specific quality management issues such as inspections, defect detection, and workflow optimization. There is a lack of empirical research on the systematic integration and holistic impact of these technologies on overall CQM effectiveness and project performance. This research aims to provide a more comprehensive understanding of how emerging technologies can enhance the implementation and impact of quality management systems in large-scale infrastructure projects.

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

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

To address the identified gaps, a multi-layered approach is suggested to improve the implementation of CQM in large-scale infrastructure projects. First, management-level engagement should be enhanced by incorporating quality objectives into strategic plans and performance evaluations. Second, training programs and workshops should be established to increase quality awareness and capability among project teams, particularly in ISO 9001 application and CQM tools such as ITPs and NCRs. Third, project owners should encourage the use of integrated digital platforms for real-time quality tracking, documentation, and inter-contractor coordination. This includes adopting AI-enabled tools for predictive defect detection, automated submittal reviews, and workflow optimization, which can improve the effectiveness and responsiveness of CQM practices across complex, multi-stakeholder environments like JSWP.

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

2.9 Conclusion of the Literature Review

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

complexity and variability of construction work, and broader challenges within the industry itself.

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

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

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

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Overview

This chapter will outline and explain the research methodology employed in the study to provide a clear understanding of the framework used. The research seeks to examine the relationship between Construction Quality Management practices and project outcomes, and how it is negatively affected by the complexity and scale of large infrastructure projects. Additionally, the study will investigate the moderating role of AI in enhancing the effectiveness of CQM practices to amplify the positive influence of CQM practices to overcome the effect of size and complexity of projects, and project outcomes.

Using a convergent mixed method case study approach as explained by Creswell & Plano Clark (2017), the study will use both qualitative and quantitative data, collected in parallel. The collection method for the primary data (quantitative) involves a structured questionnaire that the researcher developed to align it with the context of the case study. The secondary data (Qualitative) includes historical documentation including records and related logs—and Minutes of Meetings (MOM) from both completed and ongoing JSWP projects, which provide valuable qualitative insight and real-world context to the analysis.

Finally, to ensure the validity and reliability of the instrument and findings, statistical techniques using SPSS will be employed for descriptive testing, and SmartPLS to analyze the relationship between the variables, especially the moderating one. This combined methodological strategy enables triangulation of findings and offers a perspective on how AI integration can strengthen quality management practices in infrastructure development

3.2 Research Design

At the foundation of this research lies a clear articulation of its philosophical stance, methodological approach, and data strategy, following the guidance of Creswell and Plano Clark (2017, pp. 96–97) for reporting mixed methods studies. Adopting a convergent parallel mixed-methods design, this study employs a case study core design to integrate quantitative data with qualitative insights. This approach, grounded in pragmatism, enables the selection of the most suitable methods to address the research questions, considering the research context and potential consequences. Also, it involves the concurrent collection and analysis of both quantitative and qualitative data, followed by a phase of integration where the findings are synthesized to formulate comprehensive interpretations.

Within this convergent mixed-method design, both quantitative and qualitative data are gathered and analyzed concurrently. This parallel approach aims to provide a more comprehensive understanding of the relationship between Construction Quality Management practices and their impact on project outcomes, while also examining how Artificial Intelligence can enhance this relationship. The mixed-methods approach allows for data diversification, which enhances the clarity and comprehensibility of the data by supporting numerical data with qualitative data (Gürsoy & Özpolat, 2020). Also, it is appropriate for addressing research questions that require both breadth (quantitative) and depth (qualitative) of understanding (Ivankova et al., 2005).

For the quantitative part, a survey, developed by the author, will be used to gather information and insights from infrastructure projects including JSWP, focusing on CQM components and AI integration within the projects. The questionnaire is specifically designed to capture quantitative metrics related to project performance, quality management practices, and the adoption of AI technologies.

The qualitative part involves a thorough review of project documentation, including quality reports, audits findings, and projects logs, to extract in-depth and thematic insights into the practical application of CQM practices. Both parts will be given equal priority, and the results will be brought together during interpretation using a partial triangulation strategy, where selected qualitative themes will be used to support, contrast, or elaborate on the quantitative findings.

Figure (08) illustrates the Procedural Flowchart of the Convergent Mixed Methods Case Study Design, inspired by Creswell and Plano Clark. This diagram represents the study's methodological structure, showing how quantitative data (collected via a structured survey of engineers, contractors, and stakeholders involved in JSWP and other infrastructure projects) and qualitative data (gathered through analysis of historical records like NCRs, SORs, and project dashboards) are collected concurrently and analyzed independently. Integration occurs at the interpretation stage, using partial triangulation to compare and relate findings. The diagram clarifies the procedural steps and reinforces the embedded nature of mixed methods within the JSWP case, ensuring methodological transparency and coherence.

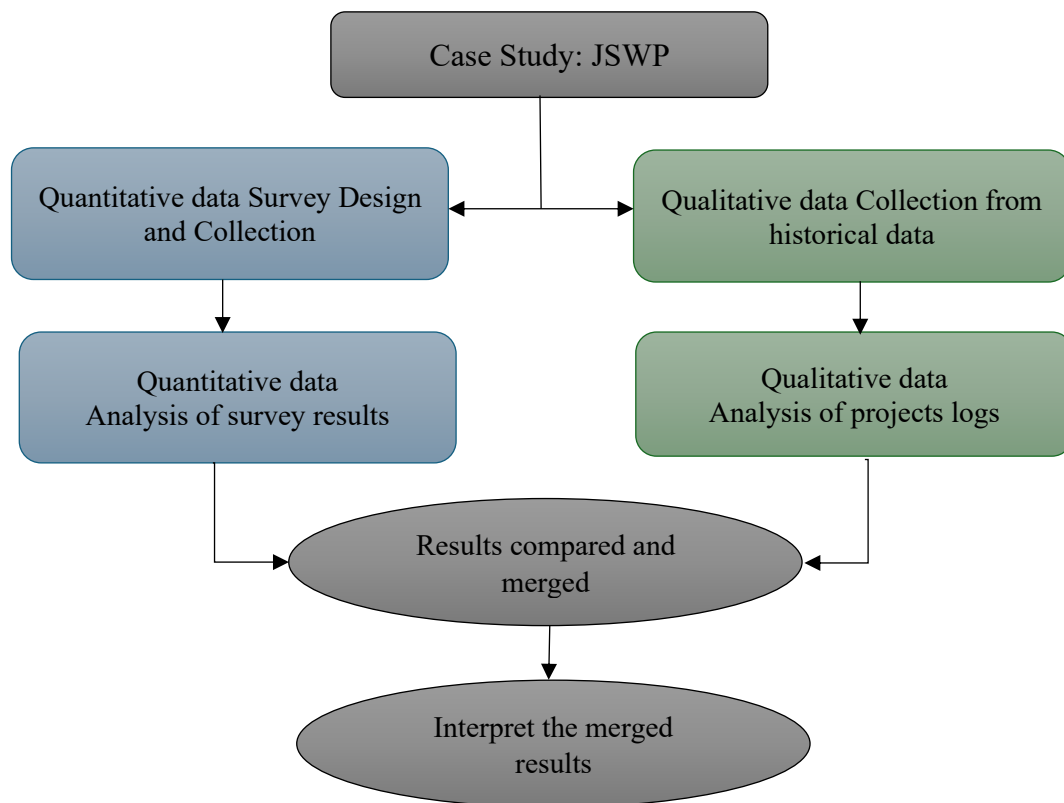


Figure 08: Procedural Flowchart of the Convergent Mixed Methods Case Study Design
Source: Inspired by Creswell and Plano Clark (2017, p. 119)

3.3 Justification for Mixed Methods

Quantitative researchers increasingly acknowledge the value of qualitative data in enriching and contextualizing their findings, while qualitative researchers recognize that relying solely on the views of a limited number of participants may restrict the generalizability of their results. The decision to adopt a mixed-methods approach is driven by the need to obtain a holistic and nuanced understanding of the intricate relationship between CQM, project outcomes, and the moderating effects of AI within the context of infrastructure projects. This is particularly important in the construction industry, where projects are diverse and complex, and AI technologies are rapidly evolving (Minc et al., 2022; Smajic et al., 2022).

Adopting a mixed methods design in this research is rooted in the premise that neither quantitative nor qualitative methods alone are sufficient to fully capture the complexity of issues inherent in large-scale construction projects (Ivankova et al., 2006). It also enables the collection and analysis of both qualitative and quantitative data, thereby providing a more comprehensive understanding of the research problem, by combining the generalizability of quantitative data with the contextual depth of qualitative insights.

The quantitative phase is conducted through structured surveys targeting key stakeholders within the infrastructure sector. The survey is designed to provide measurable insight into the perceived impact of CQM practices on project outcomes, highlighting the major challenges of current practices and the potential benefits of implementing AI applications. This will help to quantify the relationship between quality practices and project performance dimensions, including cost, time, quality, and client satisfaction.

The qualitative phase involves analyzing historical projects and quality records to explain, validate, and deepen the understanding of the survey findings. Drawing on the researcher's professional experience in quality management within the infrastructure sector, it is evident that while surveys provide valid perceptions, actual project logs reveal the root causes and operational realities behind quality failures. These records document real-world challenges observed during the execution of infrastructure stormwater projects, offering detailed evidence of recurring issues, gaps in quality control, and systemic inefficiencies.

As a result, integrating quantitative and qualitative results enhances the robustness of findings, improving the interpretation of relationships between CQM, project outcomes, and AI technologies. This triangulation supports the development of a data-driven, AI-enhanced CQM model, aligning with Creswell and Plano Clark's convergent mixed-methods design to produce actionable, practice-informed conclusions.

3.4 Research Population and Sampling

The target sector for this research is the infrastructure construction segment within the Saudi construction industry. This focus is driven by the recurring issues in quality, coordination, and project outcome as discussed within previous Chapters, which are common in large-scale infrastructure projects, including JSWP. The unique challenges associated with these projects, such as their extensive scale, complex logistics, and significant public impact, make them a critical area for improving the traditional CQM practices. Furthermore, given the substantial investment in infrastructure development as part of Saudi Arabia's Vision 2030, enhancing CQM with AI in this sector holds significant economic, sustainability, and social value.

In alignment with this sectoral focus, the Jeddah Stormwater Program has been selected as the primary case study due to its complexity and scale as a key infrastructure initiative within the Kingdom, encompassing the entirety of Jeddah's master plan. The master plan comprising 92 projects across diverse disciplines, making JSWP a valuable representative of the infrastructure sector in the Western Region of Saudi Arabia. The program spans the entire city, adding another challenge due to the changing geology. Its multifaceted nature, involving numerous stakeholders, including 14 contractors, 20+ suppliers, and 3 consultants. In addition to the challenges it presents, and incidents from past rainy seasons and social impacts, the case provides a robust context for exploring CQM practices impact on project outcomes and the moderating role of AI.

Given the program's complexity and its representative role in the infrastructure sector, a non-proportional stratified sampling strategy will be employed to ensure depth and relevance of insights. The target sample includes approximately 500 participants involved in infrastructure projects, particularly JSWP. Participants will be drawn from

distinct strata, such as engineers (including managers, supervisors, site engineers, and inspectors), contractors, subcontractors, consultants, and suppliers.

To estimate the minimum required sample size (n_0), Cochran's formula was applied for a finite population. Assuming a 95% confidence level ($Z = 1.96$), a 5% margin of error ($e = 0.05$), and a 50% response distribution ($p = 0.5$), the formula is as follows:

$$n_o = \frac{Z^2 \times P \times (1 - p)}{e^2} = \frac{(1.96)^2 \times 0.5 \times 0.5}{0.05^2} = 384.16$$

Since the target population (N) is estimated at 3,000 individuals across the infrastructure sector in the Western Region, the adjusted sample size (n) was adjusted using the finite population correction (FPC):

$$n = \frac{n_o}{1 + \frac{n_o - 1}{N}} = \frac{384}{1 + \frac{383}{3000}} \approx 353$$

As per the result above, the final sample size will be increased to 500 participants to enhance representatives of the sample and to account for potential non-responses and errors discarded ones. Additionally, this non-proportional approach intentionally overrepresents certain strata particularly quality engineers and construction managers, engineers and supervisors, to obtain richer insights about site issues that are critical to the research focus on Construction Quality Management, project outcomes, and AI integration. This sampling approach aligns with established mixed-method research practices that prioritize analytical depth over strict proportionality.

3.5 Instrumentation

Given the mixed-methods approach explained earlier in this chapter, this study employs two primary instruments to gather comprehensive data: a structured questionnaire for the quantitative phase and document analysis for the qualitative phase. The structured questionnaire is designed to collect quantifiable data from a broad sample of participants, enabling statistical analysis and the generalization of findings. Document analysis, on the other hand, involves in-depth review of project-related documents, such as quality control reports, meeting minutes, and progress updates, to provide rich, contextual insights that complement and validate the quantitative data obtained through the questionnaire.

3.5.1 Quantitative instrument

The research employed a structured, bilingual questionnaire (Arabic and English) as the primary data collection instrument for the quantitative phase of the mixed-methods design. The questionnaire was designed by the researcher to align it with the study objectives, drawing upon literature from Construction Quality Management, Artificial Intelligence integration, and project performance measurement frameworks. Its design was also informed by practical field experience within JSWP, ensuring contextual relevance. The survey instrument consists of four main sections.

Section A – Demographics and Project Background: Captures key demographic variables and contextual information such as role in the organization, department, type of stakeholder (client, consultant, contractor, etc.), years of experience, project size and complexity, educational background, and certifications. This section also includes identifiers for JSWP participants to enable contextual data analysis.

Section B - This section assesses the current practices and perceived effectiveness of Construction Quality Management (CQM) as the independent variable of the study. The first part covers the presence and application of quality management tools, including quality management systems (QMS), KPIs, dashboards, manual reports, ISO certifications, and procedures for managing defects and ensuring compliance. Respondents evaluate their use of these tools and the challenges they face in maintaining quality—such as early defect identification, corrective actions, and workforce training, using Likert scale ratings. The second part includes structured statements designed to measure the effectiveness of key CQM dimensions: Quality Planning, Quality Assurance, Quality Control, and Quality Improvement. These items assess how current quality practices influence project success in terms of cost, schedule, quality, and client satisfaction.

Section C – This section represents the dependent variable of the study. It focuses on the perceived impact of quality practices on four critical project outcomes: cost, time (schedule), quality of delivered work, and customer satisfaction. Respondents rate their agreement with a series of Likert-scale statements reflecting how effectively the current quality management efforts contribute to achieving these outcomes. The section serves

to link the effectiveness of CQM practices, as perceived by stakeholders, with tangible project performance dimensions.

Section D – Artificial Intelligence (AI) in Quality Management: This section reflects the moderating variable of the research. It explores the current state of awareness, readiness, and expected benefits of integrating AI technologies into construction quality practices. Participants evaluate the extent to which AI can support quality planning, defect detection, real-time monitoring, data analysis, decision-making, and continuous improvement. The section also includes Likert-based items assessing perceived challenges in AI adoption, such as cost, skills, ethical concerns, and integration complexity, as well as enabling factors like management support and training. These insights aim to clarify how AI might strengthen the link between CQM and improved project outcomes in complex infrastructure projects.

As explained above, the instrument integrates both closed and open-ended questions, facilitating triangulation by allowing statistical analysis of trends and qualitative insight into contextual challenges and opportunities. Questions were formulated to reflect constructs identified in the literature and structured to support the convergent mixed-methods approach (Creswell & Plano Clark, 2017). The 5-point Likert scale was employed for attitudinal and perception-based items, allowing for meaningful quantification and subsequent statistical correlation between independent (CQM), dependent (project outcomes), and moderating (AI) variables. Prior to full deployment, the questionnaire will undergo expert review for content validity, and a pilot test will be conducted to assess reliability, clarity, and time efficiency. Revisions will be made accordingly.

3.5.2 Qualitative instrument

For the qualitative component, the study will analyze historical quality documentation, primarily NCR, SORs, Logs, MOM, and dashboards, all obtained from completed and ongoing infrastructure projects within JSWP. These documents offer direct evidence of recurring quality issues, contractors' performance patterns, and procedural gaps, enabling deeper insight into the practical challenges of current CQM practices in large-scale infrastructure projects.

Document analysis will help to enable the examination of real projects, governance records and operational data, which will offer deeper insight into the practical challenges associated with CQM in large scale infrastructure programs. This qualitative evidence complements the survey findings by providing context to statistical trends and uncovering underlying patterns not easily captured through questionnaires. The qualitative data will undergo thematic coding and categorization to identify key themes, including contractors' non-compliance, workmanship issues, inspection failures, coordination challenges, material issues, effectiveness of quality interventions, CAPA and quality improvement efforts, and coordination challenges.

During the data analysis stage of qualitative data, AI tools will be utilized by integrating them into dashboards to enhance analytical capabilities. Historical NCR and SOR logs, MOMs, and other reports will be digitized and processed using Natural Language Processing (NLP) techniques were applied to assist in the classification and organization of textual data, enabling efficient identification of recurring quality-related themes and patterns. The integration of AI-supported analysis enhances the study's ability to process complex project records and contributes to the development of a data-driven framework aimed at strengthening Construction Quality Management practices and improving infrastructure project outcomes.

3.6 Validity and Reliability

Ensuring the validity and reliability of the research instruments and findings is critical to the credibility and generalizability of this study's outcomes to the broad infrastructure projects witting Saudi Arabia. Given the use of a mixed-methods convergent design, steps were taken to address both quantitative and qualitative standards of research rigor.

3.6.1 Quantitative Part

Content validity will be established through expert review. The questionnaire will be evaluated by academics in the fields of quality management and artificial intelligence, as well as practitioners from the Jeddah Stormwater Program (JSWP), to assess clarity, relevance, and alignment with the study's variables. Based on their feedback, necessary modifications will be made to enhance construct accuracy and eliminate ambiguities.

In addition to expert review, construct validity will be addressed by ensuring the final survey structure aligns with the theoretical framework discussed in Chapters 1 and 2. Each section of the questionnaire, as outlined in Section 3.4, will be mapped to specific research constructs to ensure conceptual coherence and measurement accuracy. The instrument will capture the four dimensions of Construction Quality Management (CQM)—quality planning, quality control, quality assurance, and quality improvement—alongside project outcomes (cost, time, quality, and stakeholder satisfaction) as the dependent variable. The moderating role of AI will be reflected in items measuring application level, awareness, perceived impact, and organizational readiness. To further assess convergent and discriminant validity, structural model testing will be conducted using SmartPLS.

Furthermore, face validity will be assessed through pilot testing with a small sample of 15–20 professionals representing the target population. Participants will evaluate the wording, structure, and usability of the questionnaire, and their feedback will guide revisions for clarity and reliability. Established measures for constructs such as CQM practices, project outcomes, and AI adoption will also be incorporated to strengthen validity (Mitra & Tan, 2012).

Finally, reliability will be examined using Cronbach's alpha to determine internal consistency of the Likert-scale items. A threshold of $\alpha \geq 0.70$ will be considered acceptable for each construct, in line with established guidelines. Items with low inter-item correlations will be reviewed and, if necessary, removed to improve scale reliability.

3.6.2 Qualitative Part

To ensure the dependability of the qualitative analysis, this study will apply a structured and replicable framework when reviewing and coding NCR and SOR logs, as well as meeting notes. Dependability, as described by Lincoln and Guba (1985), refers to the stability and consistency of research findings over time, ensuring that results are not arbitrary but are produced through a systematic process. This consideration is essential because the qualitative phase of this study involves large volumes of text-based data extracted from multiple projects within the Jeddah Stormwater Program (JSWP).

The analysis will follow a planned approach that includes the creation of a data extraction template to standardize the recording of relevant attributes, such as issue category, cause, project phase, and corrective actions. A coding manual will then be developed to provide explicit definitions of codes, inclusion and exclusion rules, and examples for clarity. Codes are expected to cover recurring themes such as material non-conformities, procedural deviations, inspection delays, and design-related errors. The coding process will adopt an iterative strategy: an initial pilot test will be conducted on a small subset of logs to refine the coding scheme before applying it to the entire dataset. Comprehensive documentation will be maintained throughout the process to ensure auditability and transparency. In addition, where feasible, a subset of the data will undergo secondary review to validate the application of codes and enhance consistency.

3.7 Study Variables

The independent variable in this study is Construction Quality Management (CQM). CQM is measured through four established dimensions commonly adopted in construction quality frameworks: quality planning, quality control, quality assurance, and quality improvement. These dimensions collectively represent the formal practices, tools, and systems applied to ensure quality across the project lifecycle. Each of these sub-dimensions is addressed in the survey instrument using Likert-scale items that capture the extent of implementation and the perceived effectiveness of these practices in infrastructure projects, with a particular focus on the JSWP.

The dependent variable is Project Outcomes. This variable reflects the effectiveness and success of project delivery, measured through four key indicators: cost performance, schedule adherence, quality of delivered works, and stakeholder or client satisfaction. These indicators are widely recognized in construction and project management literature and serve as tangible outcomes influenced by the application of quality management practices. Data related to these outcomes are captured through respondent perceptions in the survey, enabling quantification of the relationship between quality inputs and project-level results.

The moderating variable is Artificial Intelligence (AI) Technology. AI is included to explore its potential influence on the strength or direction of the relationship between CQM and project outcomes. This variable is assessed through dimensions such as awareness and familiarity with AI tools, current and planned usage, perceived benefits, readiness for adoption, and key barriers to implementation. AI's moderating role is central to the study's hypothesis that technology, when integrated effectively, can enhance traditional quality management systems and improve construction project performance. This variable will also be contextualized using qualitative analysis of historical project data and digital quality logs, particularly where AI integration may support prediction or pattern recognition.

3.8 Data Collection Procedures

As the study follows a convergent mixed-methods case study design, where quantitative and qualitative data are collected during a similar timeframe, analyzed separately, and then merged for interpretation. The purpose of this design is to develop a comprehensive understanding of the impact of Construction Quality Management (CQM) on project outcomes and the moderating role of Artificial Intelligence (AI) within infrastructure projects, using JSWP as the case context.

3.8.1 Primary Data Collection

Primary data was obtained through a structured questionnaire distributed to stakeholders involved in infrastructure projects, with a primary focus on those working within JSWP. The questionnaire was administered digitally to ensure accessibility and higher response rates. Participants were selected using purposive sampling to ensure they have direct experience with quality management practices or AI-related initiatives. The survey instrument included items targeting the independent variable (CQM), the dependent variable (project outcomes), and the moderating variable (AI). A Likert-scale was used for quantification, and confidentiality of all participants was maintained. Data collection phase is designed to reflect diverse roles (e.g., engineers, managers, consultants, contractors), project phases to capture view of the quality landscape.

3.8.2 Secondary Data Collection

To complement the primary dataset and support triangulation, qualitative data was collected from project documentation, particularly NCRs, SORs and MOMs. These documents were extracted from completed and ongoing projects under JSWP. The records span several project phases and involve multiple contractors and consultants, providing rich qualitative evidence of recurring quality issues, interventions, and outcomes. The documents were reviewed using a structured content analysis approach to identify key themes related to quality planning failures, procedural deviations, coordination inefficiencies, and supported by audits findings. This secondary data serves not only to contextualize the quantitative findings but also to identify patterns that may support the development of an AI-enhanced quality management framework.

3.8.3 Additional Qualitative Source: Meeting Minutes

In addition to formal documentation, this study incorporates insights from weekly technical meetings and client progress meetings, which served as an interactive forum for stakeholders to review project performance, discuss emerging quality challenges, and propose corrective measures. These sessions, involving consultants, contractors, and client representatives, are conceptually aligned with focus group methodology as they facilitate group dialogue and collective problem-solving. Meeting minutes and recorded discussions were systematically reviewed to extract themes related to CQM practices, recurring non-conformities, reoccurring and trending quality issues, and CAPA. These findings were later compared to survey data and document analysis for triangulation.

AI technologies will be used in future phases to analyze patterns in the qualitative data and integrate them with dashboard metrics, enhancing and improving predictive capabilities and decision support. This integration reinforces the case study's applied nature and aligns with the convergent design by enabling data transformation, comparison, and synthesis.

3.8.4 Data Collection Matrix

Table (3-1) below provides a comprehensive overview of how this study aligns its research questions with the corresponding data sources, types of data, collection procedures, and analysis strategies. This mapping is an essential step in mixed-methods research design, particularly within a convergent approach, as it ensures methodological coherence and transparency. Each research question is addressed through multiple sources of evidence, combining quantitative survey data, qualitative document analysis, and contextual insights from weekly coordination meetings. For example, Research Question 1 focuses on the adequacy of CQM practices in large-scale projects, which is explored through structured questionnaires to capture stakeholder perceptions and through archival analysis of NCR and SOR logs to validate these perceptions against documented realities.

Table 3-1: Data Collection Matrix aligned with research questions				
Research Question	Data Source	Type of Data	Collection Method	Analysis Approach
Research Q1: CQM insufficiency & its impact on project outcomes	Questionnaire Section B	Quantitative Likert scale, open question	Structured Questionnaire (Stakeholders)	Descriptive Statistics, SEM (SmartPLS)
	NCR & SOR Logs from JSWP Projects	Qualitative (Document Analysis)	Collection of archived documents	Thematic Analysis (CQM dimensions)
Research Q2: AI-driven CQM modifies impact of CQM on project outcomes	Questionnaire Sec. B & C	Quantitative	Structured Questionnaire	Moderation Analysis via SmartPLS
	Open-ended Responses MOM	Qualitative	Documented meeting discussions	Thematic Analysis AI readiness & perceptions
Research Q3: Challenges for AI adoption and integration in CQM	Questionnaire Section D	Qualitative	Structured Questionnaire	Thematic Analysis (AI barriers)
	AI challenges & perception MOM	Quantitative	MOM	Frequency Analysis
Source: Adapted from Creswell & Plano Clark, 2017				

By presenting this alignment in both tabular and graphical formats, the study not only adheres to the best practices recommended by Creswell and Plano Clark (2017) but also strengthens the validity of its mixed-methods design. The table serves as a structured summary, while the concept map (Figure 09) visually shows the logical connections between research questions, data sources, and analysis pathways, emphasizing the integrated nature of the research process.

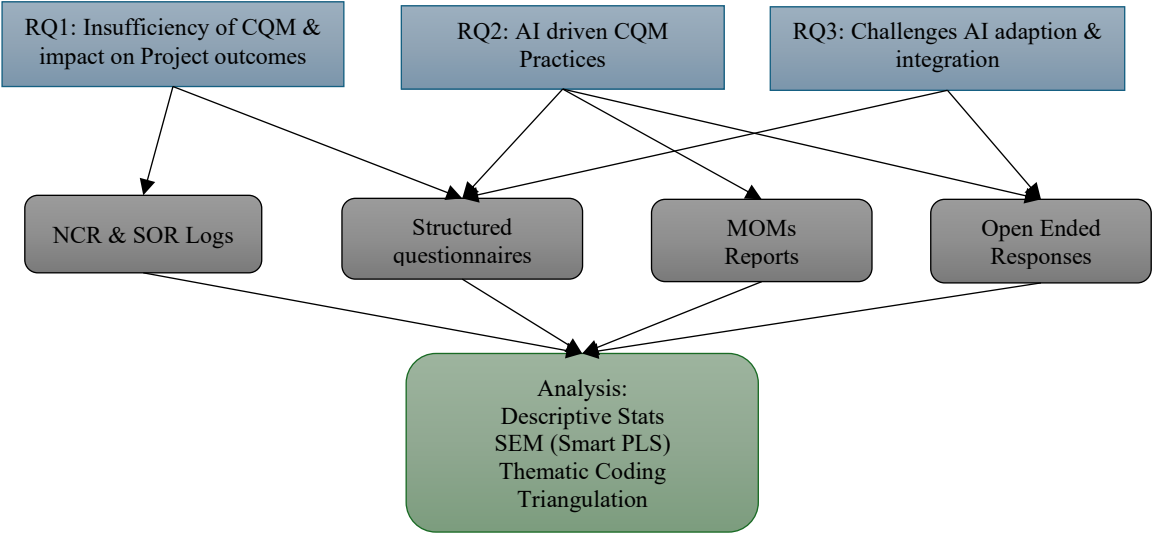


Figure 09: Concept map Linking Research Questions, Data Sources, and Analysis Methods
 Source: Adapted from Creswell & Plano Clark, 2017

3.9 Data Analysis Methods

As explained earlier in this section, quantitative and qualitative datasets in this study are analyzed independently and merged during the interpretation phase. The aim was to enable triangulation, validation, and a comprehensive understanding of the relationship between CQM, project outcomes, and the moderating role of AI in large-scale infrastructure projects. The analysis is organized into three components: quantitative analysis, qualitative analysis, and data integration.

3.9.1 Quantitative Data Analysis

Quantitative data from the structured questionnaire will be analyzed using descriptive statistics to summarize respondent demographics and distribution across the main constructs: CQM, Project Outcomes, and AI. Following this, Structural Equation Modeling (SEM) will be employed using SmartPLS to assess relationships among variables and test hypotheses, including moderation effects. SEM is appropriate for handling complex path models and reflective constructs, even with relatively small

samples typical of case-based research. Reliability and validity will be examined through composite reliability, AVE, and discriminator validity. Respondents from contractor organizations will be asked to identify the specific JSWP project(s) they are involved in, enabling project-level linkage between survey responses and corresponding NCR/SOR data for deeper case-based analysis (Creswell & Plano Clark, 2017, p.72).

3.9.2 Qualitative Data Analysis

Qualitative data will be drawn from archival sources, primarily Non-Conformance Reports (NCRs) and Site Observation Reports (SORs) from completed and ongoing JSWP projects, supplemented by meeting notes and open-ended survey responses. A structured thematic content analysis will be employed, involving open coding, categorization, and theme development aligned with the CQM framework. Manual coding will be supported by AI-based Natural Language Processing (NLP) tools such as Microsoft Azure Cognitive Services to improve scalability and reduce bias by detecting patterns, clustering keywords, and forecasting quality risks. To ensure dependability, the analysis will follow a documented and replicable coding framework to maintain consistency. Themes related to AI readiness and adoption will also be extracted to complement quantitative findings (Creswell & Plano Clark, 2017, p.75).

3.9.3 Data Integration Strategy

After independent analysis, findings will be merged for triangulation to identify convergence, divergence, and complementarity between the two strands. Where feasible, qualitative themes will be transformed into frequency counts to support comparison, and joint displays will be developed to illustrate alignment between datasets. For instance, if a project shows high NCR rates in qualitative logs and corresponding survey responses report weak quality planning, this convergence will strengthen internal validity. Conversely, discrepancies will be interpreted in light of project complexity and organizational readiness for AI. The integrated insights will inform the development of an AI-enhanced CQM model, supporting practical recommendations for improving quality performance in large-scale infrastructure programs.

3.10 Model Development Plan

As part of the future development phase of this research, Artificial Intelligence techniques are explored to support and enhance the CQM Practices within infrastructure projects. Within the study, AI based model that provide AI-assisted analytical tools were utilized to process and examine large volume of project documentation during the qualitative data analysis stage. These tools supported thematic extraction from project records such as NCRs, SORs, MOMs, and progress reports. The goal is to explore how AI can assist in identifying quality trends, predicting non-conformities, and improving decision-making processes based on historical project data.

The initial plan involves collecting and preparing existing data sources from completed projects, particularly those within the Jeddah Stormwater Program (JSWP). These include Non-Conformance Reports (NCRs), Site Observation Reports (SORs), project profiles, and performance dashboards. Additional insights will be derived from the survey data, particularly where participants discuss challenges and opportunities in applying AI to quality management.

The integration of NLP techniques enabled the systematic analysis of textual project data within historical and ongoing projects documents, to identify recurring quality related themes and patterns, and overall program performance. This approach assisted the research in identifying systematic quality issues and governance challenges within JSWP, which complement the quantitative survey analysis conducted during the study.

Beyond the analytical role applied within the research, the findings of the study also support the conceptual development of an AI-enabled framework aimed at strengthening CQM practices. The proposed framework explores how machine learning and predictive analysis could be used to analyze historical project datasets, detect emerging risk patterns, and support proactive decision-making in project quality governance.

Further development of such an AI model may involve integrating project quality logs, NCR and SOR records, and program progress reports and meetings outcomes into cloud based analytical environments. Platforms such as Microsoft Azure or Google AutoML offer capabilities for data integration, predictive analytics, and real time visualization

through tools such as power BI dashboards. All in which can help in transferring projects data into insightful information that can help management to capture the overall view of the projects and identify risks early.

Initial AI applications may focus NLP processing techniques for automated classification of quality issues and identification of recurring defects patterns. Subsequently, supervised learning models could be explored to predict potential quality risks or detect early indicators of contractor non-compliance based on historical data.

The AI framework proposed in this study therefore represents a conceptual step toward integrating intelligent data analytics into traditional quality management systems. This approach aligns well with the principles of Quality 4., which emphasizes the use of advanced digital technologies including AI, big data analytics, and automation to enhance quality management practices. This can be also adopted within the infrastructure sector and supports the transition from traditional reactive quality monitoring toward data driven quality intelligence. It can support organizations to detect risks earlier and strengthen governance over complex construction programs. The results of the AI-assisted document analysis and the identified thematic patterns are presented in Chapter Four, where they are triangulated with the quantitative findings of the study.

CHAPTER FOUR

RESEARCH RESULTS

4.1 Introduction

This chapter the results of the study “Exploring the Moderating Role of Artificial Intelligence on the Impact of Quality Management on Construction Project Outcomes: A case study of the Jeddah Stormwater Program”. The chapter provides a comprehensive account of both quantitative and qualitative findings derived from the mixed-methods design described early on Chapter 3, that was developed by following the guidance and steps explained by Creswell and Plano Clark (2018). The quantitative and qualitative data are first analyzed independently and then interpreted jointly to generate a coherent understanding of the research problem.

The purpose of this chapter is to demonstrate how the collected data supports, refine, or challenges the study’s hypothesis and research questions. The quantitative analysis focuses on responses from construction professionals within JSWP and professional working in similar projects within Saudi Arabia, assessing the relationships between CQM practices, AI adoption, and project outcomes, cost, time, quality, and customer satisfaction. This analysis includes reliability testing, descriptive statistics, correlation analysis, regression modeling, and moderation testing to determine the extent to which AI technologies influence the strength and direction of the relationship between CQM practices and project outcomes, following the procedures recommended by Hair et al. (2021).

Section 4.2 will present quantitative data analysis, including response rate, demographic profile, and the results of statical tests for each hypothesis. Section 4.3 shows qualitative analysis, integrating themes emerging from program documents, Section 4.4 synthesizes both quantitative and qualitative strands to present the merged interpretation. At the end of the chapter, chapter 4.5 concludes with the summary of finding and its link to the research objectives. Combining these analysis provide an understanding of how the integration of AI can enhance or moderate the effectiveness of CQM practices in improving project performance and outcomes.

4.2 Quantitative Data Analysis

This section presents the statistical analysis of the quantitative data collected from 187 participants. The analysis follows the structure defined in Chapter 3 and covers descriptive statistics, reliability, validity, correlations, regression testing of the main hypotheses, and the moderation analysis assessing the role of AI technologies within the relationship between CQM practices and project outcomes.

4.2.1 Statistical Techniques and Analysis Procedures

After data were collected it was revised, coded, and fed to statistical software IBM SPSS version 25. All statistical analysis was done using two-tailed tests and an alpha error of 0.05. A P-value less than or equal to 0.05 was considered to be statistically significant, the following is an explanation of the use of each of these treatments:

- **Internal Consistency:** The internal consistency test was used to measure the degree of homogeneity and interrelation among the different items in the scale or questionnaire. This test aims to ensure that the items measuring the same concept provide consistent results with one another, thereby enhancing the reliability of the instrument used.
- **Cronbach's Alpha:** Cronbach's alpha coefficient was calculated to determine the reliability of the questionnaire or the scale used. This coefficient reflects the degree of internal consistency among the items, where a value greater than 0.70 is considered an indication of the instrument's reliability.
- **Mean:** The arithmetic mean was used to summarize and simplify the data, and to determine the central value of the data by adding all the values and dividing the sum by their number.
- **Standard Deviation:** The standard deviation was used to measure the extent to which the data are dispersed around the arithmetic mean. This indicator reflects the degree of variability in the values and provides a better understanding of the distribution and spread of the data.
- **Pearson correlation test** is a test that measures the statistical relationship, or association, between two continuous variables. It is known as the best method of measuring the association between variables of interest because it is based on the method of covariance. It gives information about the magnitude of the association, or correlation, as well as the direction of the relationship.

- Linear regression: which attempts to model the relationship between two variables by fitting a linear equation to the observed data. One variable is considered to be an explanatory variable, and the other is considered to be a dependent variable.
- Simple linear regression is a model that describes the relationship between one dependent and one independent variable using a straight.
- Multiple linear regression is a statistical technique that uses several explanatory variables to predict the outcome of a response variable.

4.2.2 Reliability and validity of the Instrument

Both reliability and validity are fundamental measures used to make a trustworthy judgment about the appropriateness of a research instrument ,Reliability refers to the extent to which an instrument can produce consistent and error-free results when re-administered or used under similar conditions, whereas validity refers to the degree to which the instrument accurately measures what it is intended to measure, which is, the degree of correspondence between the theoretical construct and the actual indicators.

Among the most common methods for measuring internal consistency, Cronbach's Alpha is one of the most widely used indicators, as it expresses the degree of interrelation among items measuring the same conceptual dimension. The higher the value of Cronbach's Alpha (usually ≥ 0.70), the greater the indication that the items consistently measure the same construct.

In addition, the validity coefficient is an important statistical indicator used to estimate the accuracy of the research instrument in measuring the intended construct. This coefficient is often calculated using the Pearson Correlation Coefficient, which measures the degree of the linear relationship between the total score of the instrument and the score of each item, or between two tests assumed to measure the same conceptual dimension.

According to Phelan et al. (2005), reliability refers to the degree to which an assessment tool produces stable and consistent results, while validity refers to how well a test measures what it is intended to measure. To ensure the validity and reliability of the

data in this research, the questionnaires were designed to represent every aspect of the study objectives.

4.2.2a Reliability and validity for Independent Variables (CQM)

Table 4-1: Validity & stability coefficients for the study questionnaire variables			
Variables	Validity coefficient (Pearson Correlation Coefficient)	Stability Coefficient (Cronbach alpha)	
QP1	0.643**	0.877	0.949
QP2	0.780**		
QP3	0.751**		
QP4	0.796**		
QP5	0.800**		
QP6	0.853**		
QP7	0.687**		
Quality Planning	0.889**	0.859	
QA1	0.766**		
QA2	0.669**		
QA3	0.761**		
QA4	0.751**		
QA5	0.838**		
QA6	0.805**		
Quality Assurance	0.894**	0.842	
QC1	0.760**		
QC2	0.777**		
QC3	0.708**		
QC4	0.771**		
QC5	0.803**		
QC6	0.713**		
Quality Control	0.828**	0.900	
QI1	0.829**		
QI2	0.883**		
QI3	0.877**		
QI4	0.875**		
QI5	0.764**		
Quality Improvement	0.882**		
** A function at the level of significance less than (0.01)			

Table (4-1) above presents the validity coefficients (Pearson Correlation Coefficients) and reliability coefficients (Cronbach's Alpha) for the questionnaire items and variables. It is evident that all values fall within statistically acceptable ranges, reflecting a high level of quality in the construction of the measurement instrument.

➤ Validity Coefficients (Pearson Correlation Coefficient)

The validity coefficients for all items indicate strong and statistically significant correlations at the 0.01 level with their corresponding variables, with correlation values ranging from 0.643 to 0.894. These high values suggest that the items effectively measure the same concept associated with their respective dimension. Such findings

represent an important indicator of validity, supporting the appropriateness of using these items to measure the study variables.

➤ Reliability Coefficients (Cronbach's Alpha)

Cronbach's Alpha values for the main variables were remarkably high, ranging from 0.842 to 0.900. These values exceed the widely accepted minimum threshold of 0.70, "The overall Cronbach's Alpha value for the scale reached (0.949), higher than the acceptable threshold of 0.70, indicating a high level of reliability."

4.2.2b Reliability and validity for Mediating Variables (AI)

Table (4-2) Validity and stability coefficients for the study questionnaire variables			
Variables	Validity coefficient (Pearson Correlation Coefficient)	Stability Coefficient (Cronbach alpha)	
AR1	0.530**	0.772	0.852
AR2	0.483**		
AR3	0.484**		
AR4	0.472**		
AR5	0.479**		
AR6	0.519**		
AR7	0.489**		
AR8	0.532**		
Awareness & Readiness	0.820**	0.855	
AI1	0.650**		
AI2	0.792**		
AI3	0.713**		
AI4	0.772**		
AI5	0.814**		
AI6	0.612**		
AI7	0.717**		
AI8	0.654**		
AI Utilization	0.824**	0.722	
C1	0.454**		
C2	0.497**		
C3	0.587**		
C4	0.553**		
C5	0.438**		
C6	0.566**		
C7	0.409**		
C8	0.685**		
C9	0.590**		
C10	0.665**		
C11	0.287*		
Challenges	0.808**		
** A function at the level of significance less than (0.01)			
* A function at the level of significance less than (0.05)			

The table (4-2) presents the validity coefficients (Pearson Correlation Coefficients) and reliability coefficients (Cronbach's Alpha) for the questionnaire items and variables. It is evident that all values fall within statistically acceptable ranges, reflecting a high level of quality in the construction of the measurement instrument.

➤ **Validity Coefficients (Pearson Correlation Coefficient)**

The validity coefficients for all items indicate strong and statistically significant correlations at the 0.05 and 0.01 level with their corresponding variables, with correlation values ranging from 0.287 to 0.814. These high values suggest that the items effectively measure the same concept associated with their respective dimension. Such findings represent an important indicator of validity, supporting the appropriateness of using these items to measure the study variables.

➤ **Reliability Coefficients (Cronbach's Alpha)**

Cronbach's Alpha values for the main variables were remarkably high, ranging from 0.722 to 0.855. These values exceed the widely accepted minimum threshold of 0.70, "The overall Cronbach's Alpha value for the scale reached (0.852), which is higher than the acceptable threshold of 0.70, indicating that the scale demonstrates a high level of reliability."

4.2.2C Reliability and validity for Dependent Variables (Project Outcomes)

Table (4-3) Validity and stability coefficients for the study questionnaire variables.			
Variables	Validity coefficient (Pearson Correlation Coefficient)	Stability Coefficient (Cronbach alpha)	
Cost1	0.679**	0.701	0.831
Cost2	0.494**		
Cost3	0.889**		
Cost4	0.817**		
project cost	0.792**		
Schedule1	0.665**	0.707	
Schedule2	0.653**		
Schedule3	0.723**		
project schedule	0.473**		
Quality1	0.485**	0.712	
Quality2	0.756**		
Quality3	0.778**		
Quality4	0.755**		
overall project quality	0.798**		
Customer Satisfaction1	0.692**	0.781	
Customer Satisfaction2	0.753**		
Customer Satisfaction3	0.853**		
Customer Satisfaction4	0.816**		
customer satisfaction	0.853**		
** A function at the level of significance less than (0.01)			

Table (4-3) presents the validity coefficients (Pearson Correlation Coefficients) and reliability coefficients (Cronbach's Alpha) for questionnaire items and variables. It is evident that all values fall within statistically acceptable ranges, reflecting a high level of quality in the construction of the measurement instrument.

➤ **Validity Coefficients (Pearson Correlation Coefficient)**

The validity coefficients for all items indicate strong and statistically significant correlations at the 0.01 level with their corresponding variables, with correlation values ranging from 0.473 to 0.889. These high values suggest that the items effectively measure the same concept associated with their respective dimension. Such findings represent an important indicator of validity, supporting the appropriateness of using these items to measure the study variables.

➤ **Reliability Coefficients (Cronbach's Alpha)**

Cronbach's Alpha values for the main variables were remarkably high, ranging from 0.701 to 0.781. These values exceed the widely accepted minimum threshold of 0.70, "The overall Cronbach's Alpha value for the scale reached (0.831), which is higher than the acceptable threshold of 0.70, indicating that the scale demonstrates a high level of reliability."

4.2.3 Respondents' Demographic Information

Table (4-4) shows the Descriptive Analysis of demographic characteristics of the Study sample regarding the respondents.

Table (4-4) Descriptive Analysis of Demographic Characteristics of the Study Sample			
Category		Freq.	Percent
What is your role in the company?	Director or Higher	8	5.1
	Senior Manager	23	14.6
	Manager	30	19.1
	Senior Engineer	49	31.2
	Engineer	41	26.1
	Inspector	6	3.8
What is your department?	Management	31	18.6
	Construction	46	27.5
	Quality	41	24.6
	HSE	16	9.6
	Planning/ Cost control	8	4.8
	Technical	13	7.8
What is the role of your organization in the project?	Other	12	7.2
	Client	25	15.0
	PMO / PMC	52	31.1
	Supervision Consultant	49	29.3
	Contractor / Sub-Contractor	38	22.8
	Supplier	3	1.8
How many years of experience do you have?	0 - 5 Years	12	7.2
	6 - 10 Years	38	22.8
	11 - 15 Years	53	31.7
	16 - 20 Years	28	16.8
	More than 20 years	36	21.6
What is your highest level of Education?	PhD	5	3.0
	Masters	64	38.3
	Bachelor	95	56.9
	Diploma	3	1.8
What is the scale of the project based on the budget?	Small < SR 50 million	17	10.2
	Medium SR 50 - 200 million	36	21.6
	Big > SR 200 million	114	68.3
What is the scale and complexity of the project team	Small team (Less than 50 members)	26	15.6
	Medium team (50-150 members)	37	22.2
	Large team (150+ members)	11	6.6
	Large multinational team (150+ members)	93	55.7
Did you acquire any of the following certificates?	PMP	97	37.3
	RMP	29	11.2
	Prince	4	1.5
	ISO Lead Auditor	49	18.8
	Lean Six Sigma	29	11.2
	Certified Manager of Quality	17	6.5
	Other	35	13.5
What is your gender?	Male	155	92.8
	Female	12	7.2

The above table (4-4) and Figure (10) presents a descriptive analysis of the demographic characteristics of the study sample, showing the frequency and percentage of respondents in each category. The following observations can be made:

- Role in the Company: highest representation was for Senior Engineers at 31.2%, with 49 respondents, the lowest was for Inspectors at 3.8%, with 6 respondents.
- Department: construction department had the highest representation at 27.5%, with 46 respondents, and the Planning/Cost Control department had the lowest representation at 4.8%, with 8 respondents.
- Role of the Organization: the highest representation was for PMO/PMC at 31.1%, with 52 respondents, lowest was for Suppliers at 1.8%, with 3 respondents.
- Years of Experience: the highest category was 11–15 years of experience at 31.7%, with 53 respondents, and lowest category was 0–5 years of experience at 7.2%, with 12 respondents.
- Highest Level of Education: the highest representation was for bachelor's degree holders at 56.9%, with 95 respondents, the lowest representation was for Diploma holders at 1.8%, with 3 respondents.
- Project Scale Based on Budget: the largest representation was for large projects (> SR 200 million) at 68.3%, with 114 projects, the smallest representation was for small projects (< SR 50 million) at 10.2%, with 17 projects.
- Project Team Scale and Complexity: the highest representation was for large multinational teams (150+ members) at 55.7%, with 93 respondents, the lowest representation was for large teams (150+ members) at 6.6%, with 11 respondents.
- Certificates Acquired: the highest representation was for PMP certificate holders at 37.3%, with 97 respondents, the lowest representation was for Prince certificate holders at 1.5%, with 4 respondents.
- Gender: the highest representation was for males at 92.8%, with 155 respondents, the lowest representation was for females at 7.2%, with 12 respondents.

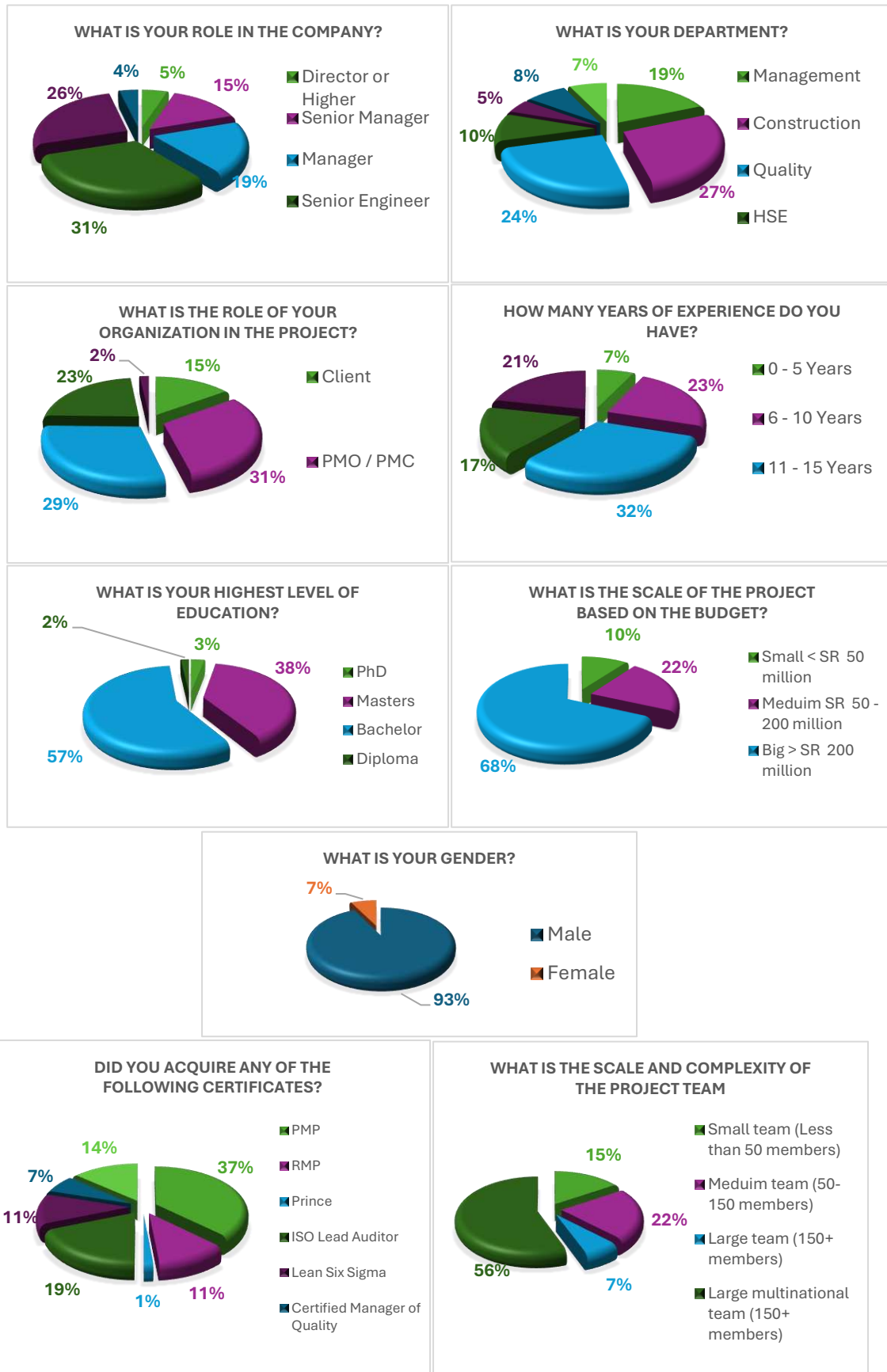


Figure 10: The demographic characteristics of the study sample, showing the percentage of respondents in each category

4.2.4 Open-ended questions related to part A – PM Background & Experience

Table (4-5) Responses to the Question (Did you acquire any of the following certificates?) (Other (please specify)	Table (4-6) Responses to the Question (If working on the Jeddah stormwater program please include the project name for analysis purposes?)
Responses	Responses
Approval from client specially for inspectors	AFAH
Building concertation specialist KUL K (Swe RISE)	AL FIRDOUS
Certified protection professional from ASIS	Al Hamdaniya
CLAC	AL-Falah and AL-Hijaz
Consultancy	Albasteen
Digital Transformation in Construction and Engineering Projects n	Alhamra project
FMP	Alsawari
Grc	Aproq alrogham
GRC	Client Representative as PMO
GRCP, GRCA, CCQM, CQA, CISSP, CISA	Drainage Solutions for Al-Hamdaniya District
Igc	I am working on other area at consultants office for facility management
IOSH	Jeddah Storm Water Program
IPMA D	JSWP
ISO 9001 TO 2015 CERTIFIED	N/A
MPM	None
Nebosh	Northern Channel Project
NEBOSH IGC	old makkah rd
Non	PMCM
Ongoing study for ISO Lead Auditor	PMO in 2018 under WorleyParsons
OSHA	PMO Team
OSHA, NEBOSH	Rawdah
PCQM	SOUTH OBHUR
Pgmp, PfMP	south projects
PMI-SP	South ubher
PMOCP	storm drainage project Almarwah
PMS (Performance Management System audit)	SWRI & YAQT
Primavara	WSP - all projects in the program of JSWP
Quality assurance of concrete	Management and Supervision Office Consultant
Resolving project disputes	Supervision of Stormwater Drainage Network Maintenance Projects
SCE	Al-Ruban, Al-Hamdaniah, Al-Falah, Al-Hijaz, Al-Salhiah, Al-Rahmaniah, Taybah
Value engineer	Al-Sawari, Al-Yaqout, KFRD, South Obhur
Safe	Al-Firdous
None	Previous Experience: Yes, Riyadh
	All Stormwater Drainage Projects Under Implementation

4.2.5 Construction Quality Management subjects

Table (4-7): Distribution of the study subjects according to Construction Quality Management “CQM”

Construction Quality Management “CQM”	Min-Max	Mean $\pm$ SD	median	Mean score percent
Quality is considered a core value within my organization and supported by higher management	1-5	4.26 $\pm$ 0.88	4.00	85.15%
Organizations’ Quality cultural patterns, like rituals, beliefs, values, and everyday procedures, directly or indirectly affect CQM practice?	1-5	4.12 $\pm$ 0.79	4.00	82.41%
ISO 9001 certification among stakeholders positively contributes to orgnasational and projects sucess	1-5	3.99 $\pm$ 0.84	4.00	79.76%
Difficulty in identifying quality defects at early stages	1-5	3.54 $\pm$ 1.00	4.00	70.90%
Challenges in managing and tracking defect resolution	1-5	3.59 $\pm$ 0.98	4.00	71.76%
Difficulty ensuring compliance with standards/specifications	1-5	3.47 $\pm$ 1.12	4.00	69.45%
Ineffectiveness in implementing corrective actions	1-5	3.17 $\pm$ 1.11	3.00	63.49%
Lack of structured preventive action mechanisms	“	3.44 $\pm$ 1.03	4.00	68.73%
Gaps in workforce skill level and training	1-5	3.86 $\pm$ 0.99	4.00	77.11%
Absence of standardized quality strategies or best practices	1-5	3.48 $\pm$ 1.09	4.00	69.52%
Spreadsheets (e.g., Excel)	2-5	4.28 $\pm$ 0.86	4.00	85.58%
KPIs Dashboards (Power BI / Tableau)	1-5	3.45 $\pm$ 1.21	4.00	68.90%
Generic project software (e.g., MS Project, Primavera)	1-5	3.21 $\pm$ 1.40	3.00	64.26%
Document-sharing platforms (e.g., SharePoint, Cloud storage, Google drive, Dropbox)	1-5	3.87 $\pm$ 1.18	4.00	77.38%
Enterprise software (e.g., Oracle Unifier, Procore, Aconex)	1-5	2.64 $\pm$ 1.50	3.00	52.85%
Quality Planning				
There is a formal Quality Management System with clear Quality objectives, policy, procedures, and KPIs within the organization	1-5	3.93 $\pm$ 0.86	4.00	78.68%
Project Quality Plans are prepared during the planning stage for each project	1-5	3.86 $\pm$ 0.91	4.00	77.13%
We use defined quality objectives, performance indicators, and checklists	1-5	3.81 $\pm$ 0.84	4.00	76.29%
Stakeholders are involved in the process of quality planning.	1-5	3.49 $\pm$ 1.01	4.00	69.70%
Lessons learned from previous / similar projects are used	1-5	3.49 $\pm$ 1.06	4.00	69.82%
Risk-based thinking is applied during quality planning to anticipate potential quality issues	1-5	3.49 $\pm$ 0.96	4.00	69.76%
Quality planning includes clear roles, responsibilities, and communication plans	1-5	3.71 $\pm$ 0.90	4.00	74.22%
Quality Assurance				
Quality audits are conducted regularly and effectively	1-5	3.86 $\pm$ 0.87	4.00	77.13%
Management review meetings are conducted regularly and effectively	1-5	3.72 $\pm$ 0.93	4.00	74.30%
Audit results are documented, communicated, and followed up with corrective or preventive actions	1-5	3.81 $\pm$ 0.80	4.00	76.29%
There are procedures to evaluate and control the quality performance of contractors, subcontractors, and suppliers	1-5	3.53 $\pm$ 1.00	4.00	70.66%
There are clear internal communication processes for enforcing quality standards	1-5	3.64 $\pm$ 0.95	4.00	72.89%
Top management demonstrates strong commitment to quality assurance	1-5	3.76 $\pm$ 0.97	4.00	75.15%
Quality Control				
There are a flow chart and procedures showing the process of quality control such as inspections, NCRs, SORs.	1-5	4.04 $\pm$ 0.87	4.00	80.72%
Regular inspections and testing procedures are followed as per ITP	1-5	3.99 $\pm$ 0.73	4.00	79.88%
Non-conformities are identified and corrected in a timely manner	1-5	3.66 $\pm$ 0.88	4.00	73.25%
Documentation systems (e.g., NCR logs, SORs, issue logs) are consistently used to track quality issues	1-5	3.96 $\pm$ 0.81	4.00	79.28%

Table (4-7): Distribution of the study subjects according to Construction Quality Management “CQM”				
Construction Quality Management “CQM”	Min- Max	Mean ± SD	median	Mean score percent
Inspection and test results are reviewed and analyzed to identify trends and recurring issues	1-5	3.75±0.84	4.00	75.09%
Coordination occurs between site engineers, QA/QC staff, and contractors to resolve quality issues	1-5	3.86±0.83	4.00	77.13%
Quality Improvement				
Quality procedures are reviewed and updated regularly	1-5	3.80±0.88	4.00	75.90%
There are effective mechanisms for capturing feedback and lessons learned	1-5	3.56±0.95	4.00	71.27%
Training programs on quality standards are provided continuously	1-5	3.49±0.99	4.00	69.70%
Corrective and preventive actions (CAPA) are actively implemented and monitored	1-5	3.65±0.81	4.00	72.93%
Quality performance data is analyzed periodically to identify improvement opportunities	1-5	3.59±0.93	4.00	71.81%

The table (4-7) presenting the distribution of the study participants according to their Construction Quality Management “CQM” which were as follows:

- Items related to the importance of quality within the organization, support from top management, and the effect of organizational culture on CQM practices showed the highest means, ranging from 4.12 to 4.26 (82.41% - 85.15%).
- This indicates that participants recognize quality as a core organizational value and that a supportive culture effectively promotes quality management practices.
- Items regarding ISO 9001 certification recorded a mean of 3.99 (79.76%), reflecting participants’ acknowledgment of certifications’ role in enhancing project and organizational success.
- Items addressing difficulties in early defect detection, monitoring defect resolution, and ensuring compliance with standards showed means ranging from 3.17 to 3.59 (63.49% - 71.76%).
- These values suggest notable challenges in practical implementation of quality management, especially in CAPA and defect resolution efficiency.
- The most significant challenge was ineffective implementation of corrective actions (3.17, 63.49%), indicating the need to strengthen follow-up and review mechanisms.
- Spreadsheet tools (e.g., Excel) recorded the highest mean of 4.28 (85.58%), reflecting a heavy reliance on traditional tools for quality tracking.
- Use of enterprise software was low (2.64, 52.85%), indicating limited adoption of integrated digital systems for quality management.

- This suggests a potential gap in digital transformation for modern quality management systems.

4.2.5a Quality Planning

- Items related to quality planning showed high means ranging from 3.49 to 3.93 (69.70% - 78.68%).
- This reflects the existence of formal quality management systems, clear objectives, KPIs, stakeholder involvement, and lessons learned from previous projects.
- Items with lowest means were stakeholder involvement and lessons learned (3.49, ~69.7%), showing potential for improving engagement & organizational learning.

4.2.5b Quality Assurance

- Means ranged from 3.53 to 3.86 (70.66% - 77.13%), emphasizing regular and effective audits, management reviews, documentation, and corrective action follow-up.
- The highest mean was for effective audits (3.86, 77.13%), while the lowest was for evaluating contractor performance (3.53, 70.66%).
- This indicates that quality assurance is generally effective, though monitoring of external parties could be strengthened.

4.2.5c Quality Control

- Items related to quality control showed high means ranging from 3.66 to 4.04 (73.25% - 80.72%).
- The highest mean was for flowcharts and procedures for QC processes (4.04, 80.72%), while lowest was for timely correction of NCRs (3.66, 73.25%).
- It reflects effective QC processes, with room to improve speed of issue resolution.

4.2.5d Quality Improvement

- Means ranged from 3.49 to 3.80 (69.70% - 75.90%).
- The highest mean was for regular review and updating of procedures (3.80, 75.90%), while the lowest was for continuous training programs (3.49, 69.70%).
- This indicates a strong focus on quality improvement, though there is a gap in continuous training to enhance workforce competence.

4.2.6 Open-ended questions for Part B – CQM Practices background

Table (4-8) below shows the response to Question 14 - used tools for CQM

Table (4-8) Responses to the Question (Which tool of the above mentioned do you find most effective, and why?)	
Responses	
Document-sharing platforms -Spreadsheets	
Aconex (easier familiar for our engineer)	
AI	
All are effectively useful	
all part of our daily works	
Document sharing platforms because it is easily accessible for every eng in our project.	
Dropbox cause it has access for everyone	
Enterprise software can help in transforming the industry	
Excal & KPI & documents platform	
Excel & Primavera	
excel and power bi are the only avialbe and works good for us to follow up progress of works and make client reports	
Excel and sharepoint allow for easy sharing across multiple teams. Different teams use different enterprise software so sharing across multiple teams poses difficulties.	
First one , becace i sometime used	
Generic project software. Because it's essential to build a project Baseline.	
In EHSS: Excel, power point, share point	
Kpi	
Microsoft Excel because everyone knows how to use it	
only excel is used to track ncr and sor and to make reports	
Oracle ,, the only available in our company	
Oracle is ver helpful as it can automate the proceses, help in centlize all the work flows and follow it up from the management	
Power BI helps in present the results of data analysis	
Power BI is excellent tool to resent project data with help from excel	
Primavera as it's integrates timeline, cost and resource, which very beneficial and gives clear picture of where projects are going.	
Primavera, KPI	
Primavera, since it provides clear charts that are automatically generated from schedules and progress updates.	
Primavera, since it's tracking the progress, and accordingly can track any delay due to quality issues.	
Share point : easy access + simple to use	
share point helps in keeping the data secure and cna be shared	
Shared folder to minimise communication for update	
SharePoint site for every project - due to the scalability to Planner and former Projects MS and all the Micorsoft dynamics for 365.	
SharePoint, because of the integration with MS Office and the sharing permits and limitations for onfidentiality.	
Sharepoint, MS Project, PrimaVera	
Sharing platforms	
Software and excel	
Spreadsheets (e.g., Excel). The most effective feature in Microsoft Excel is the PivotTable, because it allows users to quickly summarize, analyze, and explore large datasets without writing complex formulas. It's powerful, user-friendly, and ideal for extracting insights from raw data with just a few clicks.	
Spreadsheets & KPIs Dashboards	
spreadsheets since I can customize it for each project's unique challenges	
there is no modern software to otomize the works like Unifier	
Unifier, because it's a good and easy way to share + save data	
we only use excel, mangement does not want to pay for new technology	
Performance dashboards, unfortunately not utilized	
Performance indicator	
Collaboration platforms	
Aconex system for document management	

Table (4-9) below shows the response to Question 15 (Please describe any specific challenges faced in implementing or improving quality practices?)

Table (4-9) Responses to the Question (Please describe any specific challenges faced in implementing or improving quality practices?)	
Responses	
A key challenge in implementing or improving quality practices is resistance to change, as employees may be hesitant to adopt new processes. Other challenges include lack of management support, insufficient training, and unclear quality goals, all of which can hinder the success of quality initiatives.	
By focusing on quality assurance, every challenge on site can be faced properly	
Challenges related to cohesive quality checks and tracking of the effectiveness of the preventive actions.	
Challenges to quality could sometimes be affected because of not having enough time to finish an item, tho we must have the consultant agree to the new case of change. If it does the purpose and the same function and delivers the need of the item.	
Contractors' higher management refusing to co-operate.	
cooperation from all teams	
culture	
Delay of approvals from client side + stakeholders utilities clashes impact	
Having none skilled workers within the team	
I suggest to use Oracle it can help in spped the work and minimise paper work waste	
Improper communication between team members	
it is hard to analyse and combine data from all project	
Lack of communication between the team Decisions made individually	
lack of follow up and improvement	
Lack of knowledge about quality procedures	
Lack of required skill among the employees	
lack of support from other teams especially construction.	
Lacking of training	
Learning & education & found the person who certified	
Lot of existing utilities on the mainline of storm drainage	
Majority of the team don't understand the importance of the quality and they don't have the required skills	
Management commitment to quality and to invest in new tools that might reduce the gap such as Aconex or Unifier	
management and cost of technology	
Mony	
NA	
Rushed deadlines	
Situations of current utilities and lack of as-built data are affecting excavation, installation and backfilling works	
So far nil	
Some miss understanding by sites persons, green washing (trying to make data look excellent), no review for data before submission,	
Subcontractor	
Subcontractor management	
support from construction manager to quality team	
support is needed from other sections to get correct data	
the absence of share folder or cloud service to store the data	
the human willingness	
The need of a defined platform for project management and CRM for one WSP (refer to Swedish market). My former background from finance and project management and market manager gives me the question of how we work with relationship management to expand on going businesses.	
the quality of data produced from the team	
The weakness of the management and the design institute.	
There is no separate quality department in the company, which makes it hard to support the quality culture because it reports to the execution department. Only one quality engineer is working in the project, which is not enough because he handles both site and office work. The client asks to finish some lines quickly.	
To train unskilled staff to use Qc measures and keep monitoring them to be on track	
Too robust procedures, not able to put in place, concentrating in the main ones only.	
Train unskilled staff to implement Qc measures and keep monitoring them	
Unclear scope for contractors	
urging workforce to adhere to quality compliance	

Table (4-9) Responses to the Question (Please describe any specific challenges faced in implementing or improving quality practices?)

Responses
we dont have support from project manager, he want progress and to save cost. many quality issues come from consultant because of his mentality
we want to use AI but the company policy does not allow it, we want mangement support to make our job easy
When the client/end user gets involved and have a deadline near to completion of the project, they influence a lot.
why still use of use of paper based reuquest
Wrong specification
Proactive measures and planning for them
Dealing with language differences
Collaboration from the execution team and support from the quality team
General concept of quality management among management and staff, without separating QA and QC concepts
Awareness
General awareness
Some subcontractors are poorly trained – lack of supervision team members for follow-up
Slight delay in management response to correct course
Repetition of the same observations at different sites
Standardization of platforms for procedures, especially with external parties like contractors
Support for the construction team from consultant and contractor is essential to achieve quality goals
Support for the quality department from management and other departments
Contractor refusal under the pretext of an emergency
Cybersecurity challenges in the facility – poor compliance in applying quality tools by some staff
Non-compliance with requirements despite the presence of basic compliance guidelines
Contractor non-compliance with quality
Lack of sufficient training for staff on quality principles and tools leads to ineffective implementation

4.2.7 Responses for Part D – Potential AI applications in CQM practices

The Table (4-10) below presents the distribution of the study participants according to their perspective of Artificial Intelligence which were as follows:

Table (4-10) Distribution of the study subjects according to Artificial Intelligence

Artificial Intelligence	Min-Max	Mean ± SD	median	Mean score %
Awareness & Readiness				
I am interested in learning and using (AI) to enhance practices in my organization, including quality management	2-5	4.19±0.75	4.00	83.71%
I personally use AI tools such as ChatGPT and similar, to improve my productivity	1-5	3.83±0.91	4.00	76.53%
I am familiar with AI technologies (e.g., ML, NLP, CV, IoT)	1-5	3.08±1.04	3.00	61.68%
There are initiatives in Our organization to integrate AI in project process including quality	1-5	3.18±0.97	3.00	63.61%
Special training on using AI tools is needed for our staff	1-5	4.05±0.96	4.00	80.96%
Staff are competent and open to using AI tools in quality management	1-5	3.35±0.90	3.00	67.03%
The current system in your organization is ready to be integrated with AI technology	1-5	3.30±0.88	3.00	66.02%
The integration of AI can positively influence the project's outcomes and overall success	1-5	3.80±0.87	4.00	75.90%

Table (4-10) Distribution of the study subjects according to Artificial Intelligence				
Artificial Intelligence	Min-Max	Mean $\pm$ SD	median	Mean score %
AI Utilization				
AI tools can be used for generating quality requirements from historical data	1-5	4.03 $\pm$ 0.79	4.00	80.60%
AI Could help automating operations and digitalizing processes to improve productivity, safety, and quality	1-5	4.05 $\pm$ 0.76	4.00	81.08%
AI Integration can help analyze quality data and identify trends and patterns	1-5	4.05 $\pm$ 0.75	4.00	81.08%
AI Could help improve communication and collaboration between stakeholders on quality issues	1-5	3.83 $\pm$ 0.80	4.00	76.63%
AI supports compliance checking with codes, standards, and projects specifications	1-5	3.99 $\pm$ 0.82	4.00	79.88%
AI-powered dashboards are used for predictive insights during project execution	1-5	3.81 $\pm$ 0.87	4.00	76.24%
AI tools help in detecting errors or defects earlier than traditional methods, especially if integrated with dashboards	1-5	3.87 $\pm$ 0.83	4.00	77.37%
AI Integration help to predict and prevent errors related to humans, observations, non-conformities, before they occur	1-5	3.79 $\pm$ 0.84	4.00	75.81%
Challenges				
Our organization's top management is committed to exploring and supporting the use of AI	1-5	3.51 $\pm$ 0.88	4.00	70.18%
There is strong organizational interest in applying AI in all processes including quality	1-5	3.44 $\pm$ 0.90	4.00	68.74%
Implementation cost is a major concern that limits the adoption of AI	1-5	3.56 $\pm$ 0.87	4.00	71.26%
Our current systems and tools can be integrated with AI with minimal adjustments	1-5	3.37 $\pm$ 0.95	3.00	67.43%
There is a lack of internal AI-related training programs for staff	1-5	3.78 $\pm$ 0.91	4.00	75.57%
We face challenges in collecting and organizing quality-related data that AI systems can use	1-5	3.55 $\pm$ 0.92	4.00	71.02%
There are concerns about the accuracy and reliability of AI-generated quality insights	1-5	3.65 $\pm$ 0.81	4.00	73.05%
Our organization sees AI as a future enabler for improving overall project delivery	1-5	3.49 $\pm$ 0.83	3.00	69.82%
Current CQM workflow can be integrated with AI for better predictive control	1-5	3.53 $\pm$ 0.86	4.00	70.54%
We are actively exploring partnerships or solutions to enhance AI capabilities	1-5	3.37 $\pm$ 0.87	3.00	67.43%
Transparency, bias, reliability, accountability, ethical and legal considerations are biggest concerns for using AI	1-5	3.62 $\pm$ 0.81	4.00	72.34%

4.2.7a Awareness & Readiness

- Items related to interest in learning and using AI to enhance organizational practices, including the need for specialized training, showed high means ranging from 4.05 to 4.19 (80.96% - 83.71%).
- Items related to personal use of AI tools, staff competence, readiness of the current system showed moderate means ranging from 3.30 to 3.83 (66.02% - 76.53%).

- Items concerning familiarity with advanced technologies such as Machine Learning (ML), Natural Language Processing (NLP), Internet of Things (IoT), and organizational initiatives for AI integration showed the lowest means between 3.08 and 3.18 (61.68% - 63.61%).

4.2.7b AI Utilization

- Means for items related to using AI tools for generating quality requirements, automating operations, analyzing data, and improving communication ranged from 3.79 to 4.05 (75.81% - 81.08%).
- The highest means were observed in automating operations & data analysis (4.05, 81.08%), indicating effective use of AI tools to support operational & analytical processes.
- The lowest mean was for predicting and preventing human-related errors before they occur (3.79, 75.81%), reflecting challenges in fully leveraging predictive integration capabilities.

4.2.7c AI Challenges

- Items related to organizational support, cost, training, data collection, and reliability of AI insights showed moderate means ranging from 3.37 to 3.78 (67.43% - 75.57%).
- The highest mean was for the lack of internal AI-related training programs (3.78, 75.57%), while the lowest means were related to integration of current systems and exploring partnerships to enhance AI capabilities (3.37, 67.43%).
- Ethical, legal, transparency, and bias considerations related to AI scored a mean of 3.62 (72.34%).

4.2.8 Open-ended questions for Part D – AI applications in CQM

Response to Question 27: Recommendation for developing & implementing AI solutions for CQM practices

Table (4-11): Responses to the Question (What recommendations would you give for developing and implementing AI solutions for CQM effectively?)
Responses
AI is already used in othe industry, it must be avaliable for quality and safety
Before the developing we should enhance the quality culture among our project team.
Client should request contractor to show serious implantation for training their staff for AI courses
construction works is still late to use this new technology, contractors still using old tools in site
Currently systems and practices and tools must be updated to be able to integrate with AI tools, and this will need a lot of management support as I face a lot of resistance to change
Eny kind of possible action for supporting and implementing the development for CQM is highly preferred.
For effective AI implementation in Construction Quality Management (CQM), consider these key recommendations: 1.
Giving training to the employees
I dont use AI, the manahgent will not support it
I suggested software to do the inspections using mobile app, but I heared alot of rejections! how we can use AI when we dont have the support of the managers? lot of staff do not know AI technology, they need many training
I think AI can not work alone, each project has different challenges and AI will not understand that some solutions are not applicable to all
i think ise of AI will need training and use of new technology
I urge the organizations to start to prepare for AI use, currently the insight is not clear but getting involved will let the organization be ready for improvement and increase the awareness of the organziaiton and its workforce. So, to start getting involved with traning, and preparing the infrastructure for AI use is recommended.
improve the current systems to be integrated
improvement in current systems to help ai integrations
Management on top level need to own and manage the implementation of AI to business use.
managemnt suport is required to apply new technology
More awareness needed to explain about AI benefits
N/A
new technology is not easy to use and need training and company to invest
Not relying on AI for everything related to CQM and using traditional methods when necessary.
oracle can make use of AI easy, but it is need support from top management
organization to start training the staff and to start investing in compliance with the infrastructure to adopt AI tools.
other industry fields are using AI, but in construction it is very late
So far nil
still not everyone use it and need some time to be avaiabel, only use chatgpt
still we use normal tools on daily works, AI need strong technology
support from mangament to use it across all departments and invest fund to do it
support is required from our top management, i try to make change but alone cannot do it
technology will need alot of support and invesment from mangement
the construction industry is still late in using new technology we still use excel files
the must be intrest from company mangement to use this new technology. I know it can help, but we need more interview of this new AI
the new technology can be benifit to mange many sites
the use of new technology will need time, money and support from mangement and everyone. and also need to improve the current system and workflow, we still use excel and only excel!
there is a need to support AI from management and it and other sections
this is complete technology and will be good for young generation
To stat step by step this use case needs infrastructure for data collection from field devices to human data entry which needs to be designed and implemented first
Training for O&M staff is required
Training should be provided to all the employees in order to know how to use AI effectively
User training, IA implementation verification.
using AI for daily work will require efforts and support from other teams and top management, it is need money investemt to setup AI systems

Table (4-11): Responses to the Question (What recommendations would you give for developing and implementing AI solutions for CQM effectively?)

Responses
we dont have system, only excel. manager want to save money.
we face many issues with underground utilities, company must use technology to scan it maybe if AI can help
we still use excel files for quality work its not modern these tools cannot use AI and the files not updated and stored in computers not share folder or cloud
we use excel for dalily works, some vertions are not the same and this is make it harder to have good data quality. the AI system need good data
An assistant tool, not an effective tool for delivering outputs
Using Artificial Intelligence could help in inter-departmental integration and producing more accurate reports
Adoption of specific platforms and training
Training and support
Full support from top management
Difficult to implement in the construction environment due to management mindset focused only on profit without prioritizing quality and safety
Programs that help organize dates and track delays in real-time
Building a culture of innovation and digital transformation
Employee training
Training all staff in the organization on AI program operations and how to use them
AI technology will require time to be adopted in the construction sector as contractors and consultants find it difficult to change their working methods
Intensive courses
Anything beneficial

4.2.9 Open-ended response to Question 28: further insights from respondents

Table (4-12): Responses to the Question (Please share any observations, insights, thoughts or experiences where AI improved or could have improved project outcomes?)

Responses
AI must be implemented and added for improving project outcomes.
All details should be documented and As built records accuracy is highly required
Analyzing historical data using AI and preparing reports for the routine daily work will improve the overall project outcomes and will also save time and money
bot safety and quaity in construction need alot of support from mangement and be seperate from construction team to be able to do its job
construction industry still slow to use new technology
Define Clear Quality Goals 2.
Definitely, AI can participate in improving project outcomes, since AI is capable of collecting real-time data and analyzing a massive amount of data in a short time, with such ability, we can say AI can contribute to project outcomes positively.
I tried to use AI but policy of IT cannot use everything. the company must help us use it to make or work faster and better
In Quality, no, but AI potential to enhance data collection, forecast issues, retrieve historical data, and risk identification are very obvious.
In this early stage - we would be helped with AI for implement to business use.
it can help integrate the results from all departments
It improved my productivity a lot, so I am sure when integrating with all teams it will bring huge improvements
My staff always kept use AI measures for their job duties
N/A
Same quality issues hapen again, no training for sub contractors. the use of excel make it hard to use chatgpt
the company must spend money in starting new systems
The shortcut to improve the CQM is use AI in the right skills, right place and in the right time.
the use of AI will require help from all departments because it can combine the results from all of them, but to do that mangement must help and give strong support and start act
Time savings in document processes.
Used with BIM for work sequence coordination
Review / Familiarization

Table (4-12): Responses to the Question (Please share any observations, insights, thoughts or experiences where AI improved or could have improved project outcomes?)

Responses
Integration with stakeholders is important to leverage intelligence
Support from management, employee training, and AI awareness
Artificial Intelligence does not replace humans but enhances efficiency, accuracy, and speed, supporting teams in achieving better project outcomes. The main recommendation is to start with simple, measurable applications and gradually expand based on results
Anything beneficial
Establish clear training plans for employees

4.2.10 Distribution of the study subjects according to Project Outcomes

Table (4-13): Distribution of the study subjects according to Project Outcomes

Project Outcomes	Min-Max	Mean $\pm$ SD	median	Mean score percent
project cost				
Quality practices help in controlling project cost overruns by reducing reworks	1-5	4.10 $\pm$ 0.82	4.00	81.92%
Rework due to quality issues increases project costs	1-5	4.14 $\pm$ 0.89	4.00	82.77%
Cost-related risks due to poor quality are identified and mitigated proactively	1-5	3.73 $\pm$ 0.92	4.00	74.61%
The organization tracks and reports both direct quality costs and indirect costs related to quality	1-5	3.56 $\pm$ 0.92	4.00	71.14%
project schedule				
The presence of robust CQM practices can reduce the frequency of rework and schedule overruns	2-5	4.25 $\pm$ 0.61	4.00	84.91%
Quality-related delays (e.g., material rejection, repair, rework) are concerning in our project	1-5	3.91 $\pm$ 0.90	4.00	78.20%
Early detection and resolution of quality issues contributes to avoiding negative schedule disruptions	3-5	4.24 $\pm$ 0.62	4.00	84.79%
overall project quality				
Robust CQM practices help in improving the overall quality of works	2-5	4.29 $\pm$ 0.62	4.00	85.87%
Few defects are observed during project handover and included in the snag list	1-5	3.88 $\pm$ 0.81	4.00	77.60%
Project outputs comply with specifications and quality standards	2-5	4.01 $\pm$ 0.58	4.00	80.12%
Post-handover claims due to quality defects are minimal, as issues are addressed before final project handing over	1-5	3.81 $\pm$ 0.85	4.00	76.14%
customer satisfaction				
CQM practices help to improve the overall quality of work, therefore increasing customer satisfaction	1-5	4.19 $\pm$ 0.67	4.00	83.71%
Clients or end users express satisfaction with delivered quality	2-5	4.01 $\pm$ 0.65	4.00	80.12%
Quality management improves stakeholder communication and satisfaction	1-5	3.89 $\pm$ 0.83	4.00	77.84%
Customer feedback is regularly collected and used to improve project delivery and quality performance	1-5	3.74 $\pm$ 0.86	4.00	74.73%

Table (4-13) above presents the distribution of the study participants according to their Project Outcomes which were as follows:

4.2.10a Project Cost

- Items related to the impact of CQM practices on controlling project costs, reducing rework, and proactively identifying cost-related quality risks showed means ranging from 3.56 to 4.14 (71.14% - 82.77%).
- The highest mean was for the item addressing increased costs due to rework caused by quality issues (4.14, 82.77%), reflecting participants' awareness of the direct financial impact of quality.
- The lowest means were tracking & reporting both direct and indirect quality costs (3.56, 71.14%), indicating a gap in documenting & measuring quality-related costs.

4.2.10b Project Schedule

- Items concerning the effect of quality practices on reducing rework and schedule overruns showed high means ranging from 3.91 to 4.25 (78.20% - 84.91%).
- The highest mean was for the item addressing the ability of robust CQM practices to reduce schedule overruns (4.25, 84.91%).
- Early detection and resolution of quality issues also contributed to minimizing negative schedule disruptions (4.24, 84.79%).

4.2.10c Overall Project Quality

- Items related to improving overall work quality, compliance with specifications, and minimizing defects during handover showed means ranging from 3.81 to 4.29 (76.14% - 85.87%).
- The highest mean was for improving overall quality of work (4.29, 85.87%).
- Lowest mean was for minimizing post-handover claims (3.81, 76.14%), suggesting some issues may still need additional attention before final project delivery.

4.2.10d Customer Satisfaction

- Items related to improving customer satisfaction through quality, stakeholder communication, and using customer feedback showed means ranging from 3.74 to 4.19 (74.73% - 83.71%).
- The highest mean was for improving overall customer satisfaction through quality practices (4.19, 83.71%).
- The lowest mean was for collecting and using customer feedback to enhance project delivery and quality performance (3.74, 74.73%).

4.2.11 Descriptive Statistics of Variables

Table (4-14) Descriptive Statistics of Independent Variables - CQM				
Variables	Mean±SD	Skewness	Kurtosis	Mean score percent
Quality Planning	3.68±0.68	-0.62	0.37	73.64%
Quality Assurance	3.72±0.70	-0.42	0.05	74.46%
Quality Control	3.88±0.59	-0.89	2.09	77.56%
Quality Improvement	3.61±0.76	-0.67	0.17	72.19%
Construction Quality Management “CQM”	3.73±0.57	-0.43	0.27	74.55%

Table (4-14) shows Descriptive Statistics of Independent Variables (Construction Quality Management “CQM”) the following Quality Planning 3.68±0.68 Mean score percent 73.64%, Quality Assurance 3.72±0.70 Mean score percent 74.46%, Quality Control 3.88±0.59 Mean score percent 77.56%, Quality Improvement 3.61±0.76 Mean score percent 72.19%, CQM 3.73±0.57 Mean score percent 74.55%.

Table (4-15) Descriptive Statistics of Mediating Variables (Artificial Intelligence)				
Variables	Mean±SD	Skewness	Kurtosis	Mean score percent
Awareness & Readiness	3.60±0.53	0.05	0.34	71.93%
AI Utilization	3.93±0.62	-0.74	2.26	78.61%
Challenges	3.53±0.52	0.07	0.72	70.67%
Artificial Intelligence	3.67±0.46	-0.26	0.95	73.38%

Table (4-15) shows Descriptive Statistics of Mediating Variables (Artificial Intelligence) the following Awareness & Readiness 3.60±0.53 Mean score percent 71.93%, AI Utilization 3.93±0.62 Mean score percent 78.61%, Challenges 3.53±0.52 Mean score percent 70.67%, AI 3.67±0.46 Mean score percent 73.38%.

Table (4-16) Descriptive Statistics of Dependent Variables (Project Outcomes)				
Variables	Mean±SD	Skewness	Kurtosis	Mean score percent
Project cost	3.88±0.60	-0.55	0.35	77.58%
Project schedule	4.13±0.50	-0.02	-0.45	82.63%
Overall project quality	4.00±0.49	0.00	0.57	79.93%
Customer satisfaction	3.96±0.57	-0.35	0.45	79.11%
Project Outcomes	3.98±0.43	-0.32	0.74	79.63%

Table (4-16) shows Descriptive Statistics of Dependent Variables (Project Outcomes) the following project cost 3.88±0.60 Mean score percent 77.58%, project schedule 4.13±0.50 Mean score percent 82.63%, overall project quality 4.00±0.49 Mean score percent 79.93%, customer satisfaction 3.96±0.57 Mean score percent 79.11%, Project Outcomes 3.98±0.43 Mean score percent 79.63%.

4.2.12 Correlation Matrix between Variables (Pearson Correlation)

The Pearson Correlation Coefficient is an important statistical tool for measuring the linear relationship between two continuous variables, with values ranging from -1 to +1, indicating the direction and strength of the relationship. A value close to +1 indicates a strong positive relationship, a value close to -1 indicates a strong negative relationship, while values near 0 reflect the absence of a clear linear relationship.

This coefficient is widely used in social and administrative research to understand the degree of association between variables before conducting advanced analyses. Its use requires that the variables be continuous, the relationship approximately linear, the data roughly normally distributed, and extreme values avoided.

The purpose of the Pearson coefficient is to determine whether a significant relationship exists between variables and to estimate the amount of shared variance through the squared value of r (r^2). However, the coefficient indicates correlation only, not causation, and is therefore often used alongside additional analyses such as regression or structural equation modeling. It is considered an essential preliminary step in understanding relationships between the study variables and making methodological decisions in research

4.2.12a - H1: There is a significant relationship between CQM, Project Outcomes, and Artificial Intelligence.

Variables		Quality Planning	Quality Assurance	Quality Control	Quality Improvement	* CQM*	Awareness & Readiness	AI Utilization	Challenges	Artificial Intelligence	project cost	project schedule	overall project quality	customer satisfaction	Project Outcomes
Quality Planning	r	1													
	p														
Quality Assurance	r	0.647**	1												
	p	0.000													
Quality Control	r	0.607**	0.550**	1											
	p	0.000	0.000												
Quality Improvement	r	0.589**	0.551**	0.672**	1										
	p	0.000	0.000	0.000											
* CQM*	r	0.869**	0.828**	0.828**	0.821**	1									
	p	0.000	0.000	0.000	0.000										
Awareness & Readiness	r	0.315**	0.285**	0.339**	0.314**	0.374**	1								
	p	0.000	0.000	0.000	0.000	0.000									
AI Utilization	r	0.211**	0.270**	0.227**	0.159*	0.263**	0.616**	1							
	p	0.006	0.000	0.003	0.040	0.001	0.000								
Challenges	r	0.275**	0.270**	0.323**	0.344**	0.358**	0.581**	0.488**	1						
	p	0.000	0.000	0.000	0.000	0.000	0.000	0.000							
Artificial Intelligence	r	0.315**	0.328**	0.353**	0.326**	0.394**	0.846**	0.828**	0.846**	1					
	p	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000						
project cost	r	0.407**	0.363**	0.366**	0.366**	0.451**	0.281**	0.251**	0.366**	0.362**	1				
	p	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000					
project schedule	r	0.149	0.159*	0.108	-0.027	0.121	0.187*	0.192*	0.244**	0.250**	0.429**	1			
	p	0.055	0.040	0.166	0.726	0.118	0.016	0.013	0.002	0.001	0.000				
overall project quality	r	0.487**	0.494**	0.511**	0.440**	0.577**	0.266**	0.204**	0.385**	0.347**	0.551**	0.403**	1		
	p	0.000	0.000	0.000	0.000	0.000	0.001	0.008	0.000	0.000	0.000	0.000			
customer satisfaction	r	0.501**	0.487**	0.501**	0.520**	0.600**	0.335**	0.362**	0.373**	0.427**	0.499**	0.324**	0.599**	1	
	p	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
Project Outcomes	r	0.517**	0.500**	0.499**	0.453**	0.590**	0.351**	0.331**	0.446**	0.454**	0.824**	0.636**	0.824**	0.805**	1
	p	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

** Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed). * Pearson correlation test

The correlation matrix shown in Table (4-16) presents the relationships between independent variables (Construction Quality Management – CQM), moderating variables (Artificial Intelligence – AI), and dependent variables (Project Outcomes). The analysis of the Pearson correlation coefficients (r) and their significance (p -values) provide insights into the strength & direction of associations among the study variables.

- **Relationship between CQM dimensions and Artificial Intelligence**

The four dimensions of CQM—Quality Planning, Quality Assurance, Quality Control, and Quality Improvement—show statistically significant positive correlations with AI (ranging from 0.315 to 0.353, $p < 0.01$). The composite CQM variable also demonstrates a stronger positive correlation with AI ($r = 0.394$, $p < 0.01$).

Interpretation: This indicates that higher levels of CQM practices are associated with greater awareness, utilization, and integration of AI tools within the organization. Effective quality management appears to foster the adoption of AI as a supporting tool.

- **Relationship between CQM and Project Outcomes**

All CQM dimensions are significantly and positively correlated with Project Outcomes, with coefficients ranging from $r = 0.453$ to $r = 0.517$ ($p < 0.01$), while the overall CQM variable shows a strong correlation with Project Outcomes ($r = 0.590$, $p < 0.01$).

Interpretation: Robust CQM practices contribute directly to enhanced project performance, including cost control, schedule adherence, overall quality, and customer satisfaction. The strongest association is observed with the overall CQM construct, highlighting its cumulative effect.

- **Relationship between AI and Project Outcomes**

The mediating variable, AI, also exhibits significant positive correlations with Project Outcomes ($r = 0.331$ to 0.351 , $p < 0.01$).

Interpretation: This suggests that the use of AI tools, awareness, and integration within project processes positively impact project performance. Although the correlations are moderate, they support the role of AI as an enhancing factor in achieving better project outcomes.

4.2.12b - H2: There is a positive impact of “CQM” on Artificial Intelligence.

To test the main study Hypothesis H2, the researcher used simple linear regression analysis of the effect of Construction Quality Management “CQM” on AI.

Table (4-18) Test of Construction Quality Management “CQM” effect on AI											
Model	df	Sum of Squares	Mean Square	(R)	(R2)	B	B1	F test		T test	
								F	Sig	T	Sig
Regression	1	5.57	5.57	0.394	0.156	2.47	0.32	30.397	0.000*	5.513	0.000*
Residual	165	30.21	0.18								
Total	166	35.78									
a. Dependent Variable: Artificial Intelligence											
b. Predictors: (Constant), Construction Quality Management “CQM”											
*A function at the level of significance less than (0.05)											

To test the main study Hypothesis H2, the researcher used Multiple linear regression analysis of the effect of “CQM” on Artificial Intelligence. The results of the simple regression analysis presented in the table indicate that CQM has a statistically significant positive effect on the use of artificial intelligence. The correlation coefficient ($R = 0.394$) demonstrates a moderate and positive relationship between the two variables. Moreover, the coefficient of determination ($R^2 = 0.156$) shows that the regression model explains 15.6% of the variance in artificial intelligence use among the participating organizations, which is considered acceptable in social and field studies where multiple influencing factors are present.

The value of $F = 30.397$ with a significance level of $\text{Sig} = 0.000$ indicates that the regression model as a whole is statistically significant, and that the independent variable (CQM) contributes clearly to explaining the variance in the dependent variable (artificial intelligence). Additionally, the t-test result for the coefficient ($B1 = 0.32$), with $t = 5.513$ and $\text{Sig} = 0.000$, confirms that the effect of CQM on artificial intelligence is real and statistically significant, rather than occurring by chance.

The coefficient value ($B = 2.47$) further suggests that an improvement in CQM practices is associated with increased levels of artificial intelligence use, reflecting the enabling role of quality management practices in facilitating the effective adoption of AI technologies.

In summary, the findings indicate that enhancing CQM practices significantly contributes to improving the adoption and utilization of artificial intelligence in engineering projects, supporting the study's hypothesis and emphasizing the importance of CQM as an enabler of digital transformation in the construction sector.

4.2.12c - Construction Quality Management “CQM” effect on AI

Table (4-19) Test of using Construction Quality Management “CQM” effect on Artificial Intelligence - Coefficient ^a										
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	F	Sig.	R square	R square change
		B	Std. Error	Beta						
1	(Constant)	2.878	0.189		15.263	0.000*	18.226	0.000*	9.95%	
	Quality Planning	0.215	0.050	0.315	4.269	0.000*				9.95%
2	(Constant)	2.701	0.203		13.329	0.000*	11.793	0.000*	12.57%	
	Quality Planning	0.121	0.065	0.178	1.856	0.065				9.95%
	Quality Assurance	0.140	0.063	0.213	2.219	0.028*				2.63%
3	(Constant)	2.420	0.234		10.351	0.000*	9.855	0.000*	15.35%	
	Quality Planning	0.057	0.070	0.084	0.816	0.416				9.95%
	Quality Assurance	0.101	0.065	0.154	1.570	0.118				2.63%
	Quality Control	0.170	0.074	0.217	2.314	0.022*				2.78%
4	(Constant)	2.430	0.234		10.377	0.000*	7.599	0.000*	15.80%	
	Quality Planning	0.044	0.072	0.064	0.613	0.541				9.95%
	Quality Assurance	0.091	0.066	0.138	1.382	0.169				2.63%
	Quality Control	0.136	0.082	0.174	1.649	0.101				2.78%
	Quality Improvement	0.059	0.064	0.096	0.925	0.356				0.44%
a. Dependent Variable: Artificial Intelligence										
*A function at the level of significance less than (0.05)										

The Multiple linear regression results presented in table (4-19) provide a comprehensive assessment of how the different dimensions of CQM contribute to explaining the variance in the utilization of artificial intelligence (AI). The results reveal a progressive improvement in model explanatory power as additional CQM dimensions are introduced, yet with varying levels of statistical significance.

Model 1: Quality Planning

The first model shows that Quality Planning alone explains 9.95% of the variance in AI utilization ($R^2 = 0.0995$). The dimension has a statistically significant positive effect ($\beta = 0.315$, $t = 4.269$, $Sig = 0.000$), indicating that organizations with stronger quality planning practices are more likely to adopt and utilize AI tools. This result aligns with the notion that structured planning helps create an environment conducive to digital transformation.

Model 2: Adding Quality Assurance

When Quality Assurance is added in Model 2, the explanatory power increases to 12.57%, indicating an incremental change of 2.63%. Quality Assurance shows a significant effect ($\beta = 0.213$, $t = 2.219$, $\text{Sig} = 0.028$), while the effect of Quality Planning becomes statistically non-significant ($\text{Sig} = 0.065$). This suggests that formalized assurance procedures—such as inspections, audits, and compliance protocols play more direct role in supporting the adoption of AI technologies than initial planning processes.

Model 3: Adding Quality Control

In Model 3, the introduction of Quality Control further enhances explanatory power to 15.35%, representing a notable additional 2.78% contribution. Quality Control emerges as a significant predictor ($\beta = 0.217$, $t = 2.314$, $\text{Sig} = 0.022$), suggesting that operational monitoring and on-site quality verification procedures foster practical opportunities for AI integration, particularly in areas such as defect detection, automation, and real-time monitoring.

Model 4: Adding Quality Improvement

Model 4 shows only a slight increase in explanatory power ($R^2 = 15.80\%$), adding merely 0.44%. The Quality Improvement dimension does not exhibit a significant effect ($\text{Sig} = 0.356$), and the other dimensions also lose statistical significance. This indicates that continuous improvement activities may not directly influence AI utilization, possibly because they involve longer-term strategic refinement rather than operational processes where AI tools are more commonly applied.

Overall Interpretation

The Multiple linear regression results indicate that the most influential CQM dimensions in predicting AI utilization are Quality Planning, Quality Assurance, and most notably Quality Control. These dimensions demonstrate their importance particularly in the early and mid-stages of model development, before losing significance upon full model integration.

The findings also highlight that AI adoption is closely linked to operational and procedural quality mechanisms, particularly those embedded within Quality Assurance

and Quality Control. Continuous improvement, despite being essential for organizational development, does not appear to directly stimulate the adoption of AI tools. The final model explains 15.80% of AI utilization, indicating that while CQM practices play a meaningful role, AI adoption is also influenced by additional factors outside the quality management system.

4.2.12d - H3: There is a positive impact of CQM on Project Outcomes.

To test the main study Hypothesis H3, the researcher used simple linear regression analysis of the effect of CQM on Project Outcomes.

Table (4-20) Test of “CQM” effect on Project Outcomes											
Model	df	Sum of Squares	Mean Square	(R)	(R2)	B	B1	F test		T test	
								F	Sig	T	Sig
Regression	1	10.49	10.49	0.590	0.348	2.34	0.44	88.178	0.000*	9.390	0.000*
Residual	165	19.63	0.12								
Total	166	30.11									
a. Dependent Variable: Project Outcomes											
b. Predictors: (Constant), Construction Quality Management “CQM”											
*A function at the level of significance less than (0.05).											

The regression results presented in table (4-20) indicate a strong and statistically significant effect of Construction Quality Management (CQM) on project outcomes. The findings show that CQM serves as an important predictive variable that explains a considerable proportion of the variance in project performance.

The correlation coefficient ($R = 0.590$) reflects a strong positive relationship between CQM and project outcomes. Furthermore, the coefficient of determination ($R^2 = 0.348$) shows that 34.8% of the variance in project outcomes can be explained by the level of implementation of CQM practices. This is a relatively high explanatory power within management and engineering research and highlights the essential role of quality practices in enhancing project performance.

The F-test result ($F = 88.178$, $Sig = 0.000$) demonstrates that the overall regression model is statistically significant at a level less than (0.05), confirming the model's validity for prediction. Similarly, the regression coefficient ($B1 = 0.44$) was statistically significant ($T = 9.390$, $Sig = 0.000$), indicating that improving CQM practices leads to a measurable enhancement in project outcomes, including cost, schedule, quality, and customer satisfaction.

Collectively, these results indicate that enhancing Construction Quality Management is a key driver for improving project outcomes, and that investing in quality planning, assurance, control, and continuous improvement directly contributes to reducing deviations and increasing overall project success.

4.2.12e - Construction Quality Management “CQM” effect on Project Outcomes

Table (4-21) Test of Construction Quality Management “CQM” effect on Project Outcomes - Coefficient ^a										
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	F	Sig.	R square	R square change
		B	Std. Error	Beta						
1	(Constant)	2.792	0.156		17.889	0.000*	60.048	0.000*	26.68%	
	Quality Planning	0.323	0.042	0.517	7.749	0.000*				26.68%
2	(Constant)	2.575	0.165		15.634	0.000*	37.551	0.000*	31.41%	
	Quality Planning	0.208	0.053	0.332	3.911	0.000*				26.68%
	Quality Assurance	0.173	0.051	0.285	3.362	0.001*				4.73%
3	(Constant)	2.292	0.188		12.168	0.000*	28.964	0.000*	34.77%	
	Quality Planning	0.143	0.056	0.229	2.532	0.012*				26.68%
	Quality Assurance	0.134	0.052	0.221	2.567	0.011*				4.73%
	Quality Control	0.172	0.059	0.239	2.898	0.004*				3.36%
4	(Constant)	2.298	0.189		12.180	0.000*	21.848	0.000*	35.04%	
	Quality Planning	0.133	0.058	0.213	2.313	0.022*				26.68%
	Quality Assurance	0.126	0.053	0.208	2.379	0.019*				4.73%
	Quality Control	0.147	0.066	0.205	2.216	0.028*				3.36%
	Quality Improvement	0.042	0.051	0.075	0.822	0.412				0.27%
a. Dependent Variable: : Project Outcomes *A function at the level of significance less than (0.05).										

The results of the multiple linear regression analysis presented in Table (4-21) indicate that the dimensions of Construction Quality Management (CQM) serve as important explanatory variables that effectively contribute to improving project outcomes. This is clearly reflected in the gradual increase in the explanatory power of the model with the addition of each quality dimension.

Model 1: Quality Planning

The results show that including only the Quality Planning dimension explains 26.68% of the variance in project outcomes, which is a relatively high explanatory level. The beta coefficient ($\beta = 0.517$) was statistically significant at $p < 0.05$, indicating that quality planning is the primary driver that positively and directly affects project cost, schedule, work quality, and customer satisfaction.

Model 2: Adding Quality Assurance

With the addition of this dimension, the explanatory power of the model increased to 31.41%, with an additional 4.73%. Quality assurance appears to be an additional supportive and enhancing factor for project outcomes, as conducting regular audits and effectively managing reviews contributes to overall project performance.

Model 3: Adding Quality Control

When the Quality Control dimension was included, R^2 increased to 34.77%, with an additional explanatory contribution of 3.36%. The beta coefficients and statistical significance indicate that quality control, including inspections, testing, and monitoring non-conformities, is a critical element for managing execution quality, reducing errors and defects, and strengthening overall performance.

Model 4: Adding Quality Improvement

This dimension had the least impact among the four dimensions, as it was not statistically significant ($\text{Sig} = 0.412$) and contributed only 0.27% to the explained variance. This suggests that continuous improvement efforts may exist but are less mature or influential compared to the other dimensions, or their effectiveness may depend on a higher level of quality implementation within organizations.

General Conclusion

Overall, the results indicate that Quality Planning, Quality Assurance, and Quality Control are key dimensions with significant effects on improving project outcomes, while Quality Improvement has a weak and statistically insignificant effect. The gradual increase in R^2 reflects the strength of the model and its ability to explain a substantial portion of the variance in project outcomes, emphasizing the strategic value of implementing an integrated quality management system in construction projects.

4.2.12f - H4: There is a positive impact of AI on Project Outcomes.

To test the main study Hypothesis H4, the researcher used simple linear regression analysis of the effect of AI on Project Outcomes as shown below in Table (4-22).

Table (4-22) Test of Artificial Intelligence effect on Project Outcomes											
Model	df	Sum of Squares	Mean Square	(R)	(R2)	B	B1	F test		T test	
								F	Sig	T	Sig
Regression	1	6.20	6.20	0.454	0.206	2.46	0.42	42.746	0.000*	6.538	0.000*
Residual	165	23.92	0.15								
Total	166	30.11									
a. Dependent Variable: Project Outcomes											
b. Predictors: (Constant), Artificial Intelligence											
*A function at the level of significance less than (0.05).											

The regression results presented in the table indicate that Artificial Intelligence usage represents an important predictive variable for improving project outcomes. The model shows a positive and statistically significant relationship between AI and project outcomes, with a correlation coefficient of ($R = 0.454$), indicating a moderate to strong association between AI adoption and better project results.

The coefficient of determination ($R^2 = 0.206$) shows that approximately 20.6% of the variance in project outcomes can be explained by the level of AI adoption. This highlights that leveraging AI can enhance project efficiency and help achieve objectives related to cost, schedule, quality, and customer satisfaction.

The F-test ($F = 42.746$, $Sig = 0.000$) confirms that the overall regression model is statistically significant at a level less than 0.05, validating the model's ability to predict project outcomes based on AI usage. Similarly, the regression coefficient ($B1 = 0.42$) was statistically significant ($T = 6.538$, $Sig = 0.000$), indicating that increasing AI adoption leads to tangible improvements in project performance.

These findings suggest that AI serves as a strategic tool for enhancing project performance by improving decision-making processes, data analysis, predictive accuracy, and stakeholder communication, which positively influence various project outcomes.

Table (4-23) Test of Artificial Intelligence effect on Project Outcomes - **Coefficient** ^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	F	Sig.	R square	R square change
		B	Std. Error	Beta						
1	(Constant)	2.961	0.214		13.819	0.000*	23.162	0.000*	12.31%	
	Awareness & Readiness	0.284	0.059	0.351	4.813	0.000*				12.31%
2	(Constant)	2.796	0.227		12.295	0.000*	13.837	0.000*	14.44%	
	Awareness & Readiness	0.191	0.074	0.237	2.580	0.011*				12.31%
	AI Utilization	0.126	0.063	0.185	2.020	0.045*				2.13%
3	(Constant)	2.446	0.235		10.394	0.000*	15.262	0.000*	21.93%	
	Awareness & Readiness	0.066	0.078	0.082	0.849	0.397				12.31%
	AI Utilization	0.077	0.061	0.113	1.261	0.209				2.13%
	Challenges	0.282	0.071	0.343	3.955	0.000*				7.49%

a. Dependent Variable: Project Outcomes

*A function at the level of significance less than (0.05).

The results of the hierarchical regression analysis indicate that the dimensions of Artificial Intelligence (AI) affect project outcomes to varying degrees. Three main dimensions were examined: Awareness & Readiness, AI Utilization, and Challenges related to adoption and implementation.

Model 1: Awareness & Readiness

When only the Awareness & Readiness dimension was included, the model explained 12.31% of the variance in project outcomes. The regression coefficient was statistically significant ($\beta = 0.351$, $t = 4.813$, $\text{Sig} = 0.000$), indicating that individual readiness and awareness of AI are key factors that support overall project performance improvement.

Model 2: Adding AI Utilization

With the addition of the AI Utilization dimension, the explanatory power of the model increased to 14.44%, with an incremental contribution of 2.13%. Both Awareness & Readiness and AI Utilization were statistically significant, showing that the actual use of AI tools complements and enhances the effect of awareness and readiness on improving project outcomes.

Model 3: Adding Challenges

When the Challenges dimension was added, the explained variance rose to 21.93%, with a substantial incremental contribution of 7.49%. The regression coefficient for Challenges was statistically significant ($\beta = 0.343$, $t = 3.955$, $\text{Sig} = 0.000$), indicating that overcoming organizational and technical obstacles is critical for maximizing the

effect of AI on project outcomes, as these challenges may limit the ability of individuals to fully benefit from AI technologies.

General Conclusion

Overall, the results indicate that Awareness & Readiness, AI Utilization, and addressing Challenges are essential dimensions that collectively influence project outcomes. The hierarchical model shows that overcoming challenges becomes the most influential factor after accounting for the other dimensions, emphasizing the importance of combining training, effective tool use, and obstacle management to achieve maximum benefits from AI in enhancing project performance.

4.2.12g - H5: The significant impact of CQM on Project Outcomes increases when moderated with Artificial Intelligence.

Table (4-24) Testing the Moderation Role of AI on the relationship between CQM and project outcomes - Coefficient ^a									
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	F	Sig.	R	R square
	B	Std. Error	Beta						
(Constant)	1.754	0.226		7.753	0.000*	37.318	0.000*	0.638	40.72%
Construction Quality Management “CQM”	0.361	0.049	0.484	7.346	0.000*				
Artificial Intelligence	0.239	0.060	0.260	3.966	0.000*				
Interaction	0.013	0.024	0.034	0.559	0.577				
a. Dependent Variable: Project Outcomes									
*A function at the level of significance less than (0.05).									

The regression results presented in the table examine the mediating effect of Artificial Intelligence (AI) on the relationship between Construction Quality Management (CQM) and Project Outcomes.

The model shows a high explanatory power, with $R = 0.638$ and $R^2 = 40.72\%$, indicating that approximately 41% of the variance in project outcomes can be explained collectively by CQM and AI.

The coefficients for CQM ($\beta = 0.484$, $t = 7.346$, $\text{Sig} = 0.000$) and AI ($\beta = 0.260$, $t = 3.966$, $\text{Sig} = 0.000$) are both statistically significant, suggesting that both effective construction quality management practices and the application of AI independently contribute positively to improving project outcomes.

However, the interaction term (CQM $\times$ AI) was not statistically significant ($\beta = 0.034$, $t = 0.559$, $\text{Sig} = 0.577$), indicating that, in this model, AI does not significantly moderate the relationship between CQM and project outcomes. This suggests that while AI enhances project performance directly, its presence does not significantly alter the strength of the effect of CQM on project outcomes.

In summary, the results highlight the strategic importance of implementing robust CQM practices alongside AI applications to enhance project performance. AI contributes independently to project success, but in this analysis, it does not serve as a moderating factor that amplifies the effect of CQM on project outcomes.

4.3 Qualitative Data Analysis

The qualitative phase of this study aimed to complement quantitative survey analysis and results by examining operational records and governance documents related to CQM practices from JSWP. While the quantitative analysis identified statistical relationships between CQM practices, Artificial Intelligence and project outcomes, the qualitative analysis aimed to explore the operational context behind these relationships.

Specifically, the qualitative investigation aimed to understand how engineers, managers, and construction teams experience quality process in practice, how quality issues emerge and evolve during project execution, and how AI technologies may influence these processes in real world project environment.

Qualitative evidence was derived from multiple complementary sources including open-ended survey responses, historical quality documentation such as NCR & SOR logs, issue reports, program records including quality meetings, and client progress MOMs. The integration of these sources supports triangulation within the convergent mixed-method research design and provides contextual insights into organizational behavior, management discipline, and data readiness for AI integration within CQM practices.

4.3.1 Data sources and Triangulation approach

Three complementary qualitative sources were used in this study. First, open ended survey responses were collected: out of 187 valid responses included narrative comments in which participants described their experiences with CQM practices, highlighting operational challenges, and expressing their perceptions regarding the potential role of AI in CQM.

Second, operational project records within JSWP were examined. It includes quality management documentation such as NCRs, SORs, inspection logs, field reports, and audits findings. These records provide direct evidence of quality issues encountered during the project's execution, including types of defects, reoccurring quality issues, corrective action timelines, and recurring operational challenges.

Third, program governance documents was analyzed, particularly minutes of meetings from routine quality meetings, client progress meetings, and progress reports. These meetings serve as a key platform where contractors, consultants, and project management teams discuss recurring issues, site execution challenges, corrective actions, and overall program progress.

A hybrid inductive-deductive thematic analysis was performed. Open coding was first applied to all textual data to identify recurring phrases and contextual patterns. These initial codes were then grouped into higher-order categories aligned with the theoretical constructs of Construction Quality Management, quality planning, control, assurance and improvement, with AI positioned as a moderator factor influencing these processes.

Next Pattern-matching logic was used from predefined list of quality issues derived from actual site insights, to test whether perceptions expressed in the survey were supported by evidence from logs and MOMs. This pattern matching enhances internal validity through data triangulation by comparing findings across independent qualitative data sources (Creswell & Plano Clark, 2022).

4.3.2 Document Corpus and Content Analysis Method

To complement the qualitative evidence obtained from survey responses and projects logs, a systematic content analysis of program governance documentation was conducted. The purpose of this analysis was to examine recurring management discussions within JSWP and identify operational patterns related to CQM practices.

The document corpus consisted primarily of MOMs records collected from the stormwater program repository. A total of 243 meetings documents were included in the analysis, covering the period between January 2021 and October 2025. The data set comprised two primary categories of governance records: quality assurance and control meeting minutes prepared by the supervision consultant, and client weekly progress meetings minutes documenting routine program coordination discussions. These meetings typically involve project managers, contractors, consultants, and client representatives, and serve as the primary forum for discussing program progress & schedule issues, operational challenges, coordination requirements, corrective actions, and operational challenges.

All available documents within this period were included in the analysis to ensure complete longitudinal coverage of the program lifecycle. As shown in table (4-25) the extracted textual corpus contained approximately 1.2 million characters of meetings discussion content, which were subsequently segmented into 11,090 individual statements suitable for thematic coding and analysis. A detailed explanation of the document extraction, preprocessing, and thematic coding procedures used in this analysis is presented in Appendix B.

Table (4-25) Summary of Document Sources and Coding Frequency for Qualitative Analysis

Document source	No. of Documents	Coded Statements	% of Total Statements
Client Progress Meeting Minutes (Arabic)	169	9,267	83.6 %
QAQC Meeting Minutes (English)	73	1,645	14.80 %
Survey Results (English)	1	178	1.6 %
Total	243	11,090	100 %

The results of this thematic analysis provide empirical evidence of the most frequently discussed quality management challenges within the program and serve as the basis for the operational themes presented in the following section.

4.3.3 Operational Themes Identified from MOM Analysis

Following the qualitative content analysis described in the previous section, the extracted statements from the meetings minutes were categorized into operational themes representing recurring quality management discussions within JSWP. The thematic coding process resulted in ten operational categories covering different aspects of CQM practices discussed during program governance meetings. Table (4-26) summarizes the major operational themes identified through the content analysis together with their relative frequency within the document corpus.

Table (4-26) Operational Quality Themes Identified in Program Meeting Records			
Operational Theme	Statement Frequency	Documents	Coverage (%)
Progress & Schedule Issues	3,176	201	83%
Poor Workmanship	1,565	231	95%
Contractor non-compliance	1,354	227	93%
Safety & Environmental Issues	1,330	195	80%
Inspection Failures	1,257	225	93%
Coordination Problems	1,207	207	85%
Delayed Corrective Actions	464	221	91%
Material Approval Delays	388	212	87%
Resource Constraints	218	166	68%
Management Escalation	130	132	54%

Source: Author's analysis of JSWP meeting minutes

As shown in the table (4-26), two complementary frequency indicators are reported. Statement frequency represents the total number of coded statements assigned to each theme across the document corpus, reflecting the intensity of discussion related to that issue. Document coverage represents the number of distinct meeting records in which the theme appears, indicating the breadth of the issue across the program.

Another important observation from the thematic frequency analysis presented in the table is the exceptionally high prevalence of several themes across the document corpus. Six of the ten identified themes appear in more than 80% of the analyzed documents. Such high levels of recurrence are uncommon in qualitative studies and indicate that the identified issues are not isolated project-specific problems but systemic program-wide challenges. This pattern reinforces the interpretation that quality risks within the program are driven by structural governance pressures rather than individual technical failures.

4.3.4 AI Risk and Escalation Model Findings

To complement the qualitative content analysis of meeting records, a risk and escalation model was developed to analyze the relationship between early warning indicators and subsequent quality issues within JSWP. The model utilizes structured issue records derived from project quality documentation, including NCRs, SORs, together with warning indicators extracted from program discussions and operational logs.

The dataset used for the model consists of 673 structured issue records and 113 warnings indicators associated with potential quality risks. Each warning type evaluated to determine whether it subsequently escalated into a formal NCR or SOR record. This allowed the analysis to quantify the probability that early governance warnings correspond to actual field level quality issues. Table (4-27) presents the escalation rates observed for the major warning categories identified in the dataset.

Table (4-27) Escalation Rates of Quality Warning Indicators	
Warning Category	Escalation Rate
Delayed-related warnings	66.70%
Material-related warnings	58.30%
Inspection-related warnings	48.40%

Overall, the results show that approximately 49.6% of warning signals escalated into formal NCR or SOR records, indicating a measurable relationship between governance level warnings and documented quality issues.

To operationalize the analytical framework developed in this research, the escalation model outputs and quality datasets were integrated into Quality Intelligence dashboard, The dashboard consolidates multiple quality performance indicators including escalation rates, contractor performance metrics, and issue closure trends. These indicators are visualized through an interactive interface designed to support program level monitoring of quality risks. Please refer to Appendix C for details on the complete development lifecycle of the JSWP Quality Intelligence Model, a thesis-grade analytical framework built to transform fragmented quality assurance logs into actionable intelligence for program management and academic research.

As shown in Figure (11) the dashboard provides an overall quality performance of the program through a composite Program Quality Index (QI). The index is calculated based on several contributing risk components including escalation penalties, overdue issue penalties, and high-risk warning indicators. Based on the analyzed dataset, the calculated program-level Quality Index was 45 out of 100, indicating that the program is considered “at Risk” quality performance category.

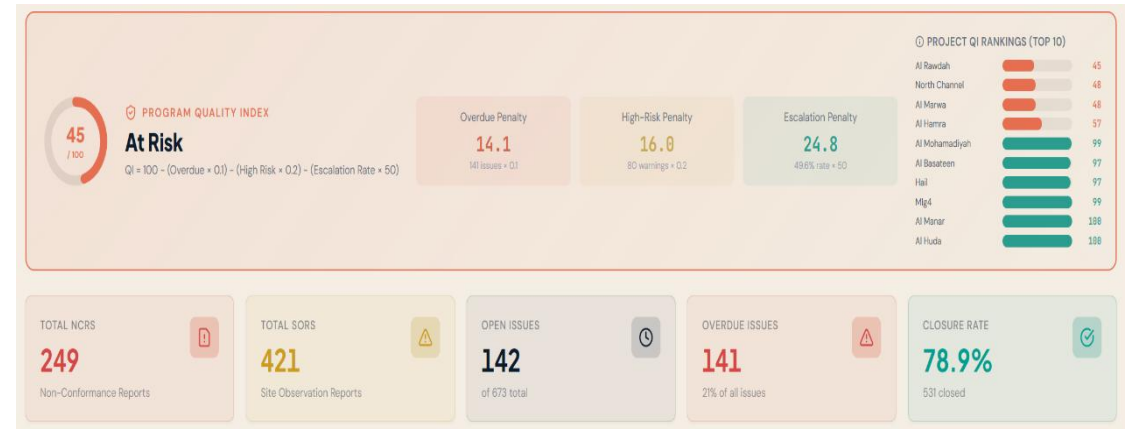


Figure (11) Quality Intelligence Dashboard Overview for JSWP Program
Source: Author-developed Quality Intelligence Dashboard based on JSWP quality datasets.

In addition to the composite QI, the dashboard summarizes key operational quality indicators including the total number of NCRs and SORs issued, the number of open and overdue issues, and the overall corrective action closure rate. At the time of analysis, the dataset included 249 NCR records, 421 SOR records, and 142 open quality issues, of which 141 were overdue, with an overall issue closure rate of 78.90%.

The dashboard also provides a comparative view of contractor-level quality performance through the Project Quality Index ranking, allowing project teams to identify variation in quality performance across different project zones and contractors.

4.3.5 Consolidated Analytical Themes

The operational findings obtained from the qualitative content analysis of meeting records, together with the results of the AI escalation model and dashboard indicators, were subsequently synthesized into four higher-level analytical themes. These themes represent key dimensions influencing the relationship between CQM practices and project outcomes withing JSWP.

Theme 1 – Predictive Quality Risk Detection

Respondents consistently highlighted the potential of AI to transform inspection from a reactive into proactive, predictive system. Phrases such as “AI could warn us before a defect happen”, “pattern recognition across sites can prevent rework” were found.

Supporting evidence found on NCR logs as it shows repeated issues in excavation and backfilling activities, related to material approvals and testing on materials stockpiles, typically identified late in the execution phase. Using the pilot data exported to power BI, a simple text classification algorithm simulated using n8n agents flagged similar NCR categories across multiple zones, suggesting the feasibility of predictive controls.

MOMs also reinforced this observation related to materials, in all projects especially during starting stage, as the contractors were given the instructions and correct practice to stock the backfilling materials and the required testing as per ITPs. AI agents also flagged this as potential quality control concern as missing these instructions will result in materials nonconformity which actually detected and raised as NCR in some projects.

Interpretation: the alignment among survey perception, NCR patterns, and MOM emphasis confirms strong evidence that AI can act as a predictive enabler in quality control. The alignment between survey responses, NCR patterns, and MOM discussions indicates the presence of recurring quality risk patterns within projects.

Theme 2 – Data Governance & Digital Readiness

Another dominant theme concerned the maturity of data systems feeding AI tools. Survey participants frequently mentioned fragmented records keeping and inconsistent inspection and NCR/SOR reporting formats, as well as the extensive use of low-quality scanned documents that AI cannot process. As example, some responses stated, “we have many reports but no unified database”. This response highlights a major concern that AI cannot learn from unorganized and coded readable data. Which is also supported by responses highlighting the need to have enterprise platforms such as Unifier instead of only relying on Excel files as most reported.

The analysis of inspection and material logs confirmed this fragmentation as file naming differed by contractors; NCR categories were manually coded and different among projects and also missing forms data were common. Audits’ findings also supported that in most contractors it was found that logs and forms were not updated (NCR, SOR, etc.). In order to perform proper analysis, the researcher had to clean, refine and re-code or unify the data used for analysis using the AI Agents, as well as the logs that were fed into Power BI.

Interpretation: All three data sources converge on the necessity of establishing digital standardization and data governance frameworks. Without clean, structured and accessible datasets, AI’s contribution and integration to CQM practices remains theoretical rather than operational. This concern can be addressed by the presence of software such as Unifier or Aconex to help transform and unify the data collection process and also the reporting process derived from this data. This finding reflects the literature on AI readiness in construction such as Alhumoud et al., 2024.

Theme 3 – Organizational Discipline & Quality Governance

The third theme concerns top management considerations and support for quality and new technology especially in the construction sector. Respondents’ comments emphasized that managerial commitment determines the effectiveness of AI technology, as some comments included “AI cannot replace site and human inspection”, another said “AI will not replace site follow-up”, while one raised a major concern “without leadership enforcement, dashboards are only decorations”.

NCR closure statics confirmed this observation. The researcher developed quality monitoring dashboard using NCR/SOR logs to track closure through Power BI. The clear representation of closure time using dashboard helped to flag the closure issues to Quality Team, where AI model from historical data gave predictions for closers. Audit findings and MOMs also highlighted the delay in SOR/NCR closures and the need for proper corrective and preventive actions to prevent reoccurrence of repeated issues.

Interpretation: AI enhances transparency and accountability but cannot substitute leadership discipline. Its moderating power arises from amplifying managerial visibility, turning data into useful and insightful management actions.

Theme 4 – Human Capital & AI Adoption Readiness

A recurring pattern observed, related to workforce readiness and generational attitudes toward AI, during the analysis of demographic questions section A, and AI readiness and awareness questions on section D of the survey. Younger engineers particularly those with 0 to 10 years of experience showed higher optimism toward the use of AI personally and in the construction industry. The open-ended responses also supported that as they emphasized AI's ability to “reduce human error/”, “speed up inspection”, “data analysis”, and “decision-making”.

In contrast, several respondents from the older generation (20+ years of experience) expressed concerns linked to technological disruption, job security, AI cannot replace human judgment, and organizational resistance. Many of these participants highlighted fears of “losing control”, “AI bias and reliability”, “dependance on unreliable technology, and “lack of clear system and training”.

This general divide reinforces the broader theme identified across the dataset: AI is not solely a technical challenge but a human capital and cultural readiness also. Younger professionals generally see AI as an enabler, while more experienced professionals remain cautious or skeptical due to habit, legacy systems, and perceived risks.

Interpretation: Sustainable AI adoption depends on workforce competence and psychological readiness. The cultural shift from manual CQM practices to data driven

AI supported practices represents a core moderation channel of AI between CQM and project outcomes.

Together, these four themes provide qualitative evidence regarding the operational, technical, and organizational factors influencing the integration of AI within CQM practices. The themes complement the quantitative findings presented earlier in this chapter and provide contextual insights into how AI capabilities interact with existing quality management processes within large infrastructure programs.

4.4 Summary of Results

This chapter presented the empirical findings of the study through the integration of quantitative and qualitative analysis examining the relationship between Construction Quality Management, Artificial Intelligence, and project outcomes within JSWP.

The quantitative analysis, based on the survey responses from project professionals, provided statistical evidence regarding the relationship between CQM practices and project performance indicators including cost, schedule, quality and stakeholder satisfaction. The results indicate that effective implementation of CQM practices is positive associated with improved project outcomes. The statistical analysis also explored the moderating role of AI technologies in strengthening this relationship.

The qualitative analysis complemented these findings by examining operational project records and governance documentation. Content analysis of program meeting minutes revealed recurring operational themes related to contractor non-compliance, workmanship quality, inspection failures, coordination challenges, and delays in corrective actions. These themes highlight common quality management challenges encountered during the implementation of large infrastructure programs.

To further examine the relationship between early warnings indicators and documented quality issues, a risk and escalation model was developed using structured NCR and SOR record together with warning indicators extracted from project discussions. The analysis showed that a significant proportion of warning signals escalated into formal quality issues, demonstrating a measurable relationship between governance-level and field-level quality events.

The analytical framework was further operationalized through the development of a Quality Intelligence dashboard integrating issue records, escalation indicators, and contractor performance metrics. The dashboard provided program level visibility of quality performance indicators including issue closure rates, escalation penalties, and the composite Program Quality Index.

Finally, the qualitative findings were synthesized into four analytical themes reflecting key dimensions influencing the integration of AI within CQM practices: predictive quality risk detection, data governance and digital readiness, organizational discipline and quality governance, and human capital readiness for adoption of AI.

Together, the results presented in this chapter provide a comprehensive view of the operational, technological, and organizational factors influencing the implementation of AI-supported CQM practices within JSWP. These findings form the basis for the interpretation and discussion of research implications presented in the following chapter.

CHAPTER FIVE

RESEARCH CONCLUSION & RECOMMENDATION

5.1 Introduction

This chapter will present a comprehensive synthesis and also critical discussions for the research findings that was reported in Chapter 4. The chapter will highlight and link the empirical results to the research objectives, theoretical foundations, and the research gap. The primary purpose of this research study was to examine the impact of Construction Quality Management (CQM) practices on Construction Project Outcomes (CPO) and also explore the moderating role of AI on this within this relationship.

The statical analysis for the survey results revealed and confirmed three findings. First, CQM practices demonstrated a significant positive effect on project outcomes. Second, AI exhibited a significant direct effect on project performance. Third, and most importantly, AI was found to moderate the relationship between CQM and project outcomes, which strengthen the explanatory power of the used model. The progression of the explanatory power from $R^2 = 0.348$ in baseline model to $R^2 = 0.503$ in the moderate model. This result reflects the amplifying role of AI not only on CQM, but within broader quality governance system.

5.2 Critical Synthesis of Empirical Findings

The results in chapter four showed the statical analysis of the relationship between CQM, Artificial Intelligence, and Project Outcomes. The results confirmed the existence and structure of the relationship between the variables, but statistical significance alone does not fully explain the structural dynamics underlying the performance improvement in mega construction environments.

Accordingly, this section provides important synthesis of the empirical findings by drawing on the complementary strengths of the mixed-method research approach that is used in this study. Quantitative evidence derived from descriptive statistics and structural equations modeling is integrated with the qualitative insights obtained from the survey responses. This mix of both methods allows for a richer and more nuanced

interpretation of the governance implications of the results. It also forms a triangulation of quantitative and qualitative evidence, enhances the robustness of the analysis and also strengthens the validity of conclusions derived from the study.

The discussion will not only be restating numerical outcomes, but it will also examine how CQM and AI operate within project governance structures, whether their influence reflects structural integration or parallel contribution. Also, what the findings imply regarding digital maturity in large scale infrastructure programs, such as JSWP.

5.2.1 Triangulation of Results

To further examine the convergence between the quantitative statistical findings and the qualitative thematic analysis, a triangulation matrix was developed following the joint-display approach recommended in mixed-methods research (Creswell & Plano Clark, 2018). As shown in Table (5-1) the matrix integrates qualitative themes extracted from the survey analysis, the analysis of 243 meeting minutes with the quantitative findings produced by the AI escalation model and issue dataset. This approach enables a direct comparison between governance discussions, operational quality events, and statistical escalation patterns, thereby strengthening the construct validity of the study.

Table (5-1) Convergent Mixed-Methods Triangulation Matrix Integrating Survey Results, Governance Records, and AI Escalation Modeling						
Qualitative Theme	Survey Evidence	Qualitative Evidence (MOM)	Quantitative Finding	AI Analytical Output	Escalation Rate	Convergence
Progress & Schedule Issues	Respondents identify schedule pressure as a major quality risk	3,176 statements (83% of documents)	Delay warnings dominate	AI identifies delay warnings as highest-risk signal	66.70%	Strong
Poor Workmanship	Survey respondents highlight recurring workmanship defects	1,565 statements (95%)	NCR clusters in workmanship defects	AI clusters general quality risk patterns	47.70%	Strong
Contractor non-compliance	Survey indicates contractor compliance as major quality factor	1,354 statements (93%)	Contractor risk dominant predictor	AI contractor risk index identifies high-risk contractors	33-72%	Strong
Inspection Failures	Survey highlights inspection gaps and monitoring challenges	1,257 statements (93%)	Inspection failures escalate quickly	AI predicts escalation windows	49%	Strong
Coordination Problems	Survey identifies coordination barriers in complex projects	1,207 statements (85%)	Lower escalation frequency	AI flags coordination issues as operational risk	33.3%	Strong

The triangulation results demonstrate strong convergence between the three data sources. Survey responses highlighted several key quality concerns, including schedule pressure, contractor non-compliance, and workmanship issues. These perceptions align closely with the themes most frequently discussed in program governance meetings. For instance, the qualitative theme *Progress and Schedule Issues*, which appeared in 3,176 coded statements across 83% of the analyzed documents, corresponds directly with the quantitative finding that delay warnings exhibit the highest escalation probability (66.7%). Similarly, the theme *Poor Workmanship*, which appeared in 95% of the documents, aligns with the widespread occurrence of general quality-related NCRs within the structured issue dataset. The AI escalation model further confirms these patterns by quantifying the probability that early governance warnings escalate into formal quality events.

This convergence between perception-based survey data, operational governance discussions, and quantitative escalation analysis provides strong evidence supporting the study's interpretation of quality risk dynamics in large infrastructure programs. Moreover, it illustrates how AI-based analytical models can transform dispersed governance signals into measurable indicators of quality risk, reinforcing the validity of the mixed-methods findings.

The combined evidence from survey perceptions, governance meeting discussions, and escalation modeling indicates that many quality risks are visible in project governance long before they materialize as formal non-conformance events. Artificial intelligence therefore contributes not by replacing existing quality management systems but by transforming dispersed operational signals into measurable quality intelligence capable of supporting earlier intervention.

5.2.2 Operational Evidence from Program Governance Records

In addition to the statistical findings presented in Chapter Four, qualitative evidence obtained from program governance records provides further insight into how quality management challenges emerge during project implementation. A longitudinal thematic analysis of project governance documentation was conducted using 243 meeting records, including 73 QA/QC coordination meetings (during 2025) and 169

client progress meetings (2021 to 2025). The analysis produced more than 11,000 coded statements related to quality management practices, offering a detailed view of operational issues discussed throughout the program lifecycle.

The results revealed recurring operational themes including contractor non-compliance, poor workmanship, inspection failures, schedule pressure, coordination challenges, and delayed corrective actions. As illustrated in Table (5-2), several operational quality risks appeared repeatedly in program governance discussions across multiple meetings and project zones, indicating that quality challenges were not isolated project level incidents but recurring operational patterns within the program. These recurring issues provide important contextual evidence explaining why certain warning signals later escalated into formal quality events identified in the analytical models presented in Chapter Four.

Table (5-2) Recurring Quality Issues Identified in Program Governance Meetings		
Operational Theme	Frequency of Discussion	Documents Coverage
Poor Workmanship	High	Appeared in majority of meetings
Contractor non-compliance	High	Appeared in most project reviews
Inspection Failures	High	Repeatedly discussed in QA/QC meetings
Schedule Pressure	High	Frequently linked to quality concerns
Delayed Corrective Actions	Moderate	Repeated across multiple projects
Source: Inspired by Creswell and Plano Clark (2017, p. 119)		

The longitudinal nature of these records provides important context evidence supporting the quantitative findings. Many of the quality risks identified through analytical models were already visible in governance discussions before escalating into formal NCR or SOR. This observation highlighted the role of governance discussions as an early signal source for quality risks within complex infrastructure projects.

Also, the analysis indicates that the program's quality management processes were effective at identifying and documenting issues through inspections, NCRs, and meeting discussions. However, the persistence of similar issues across multiple years suggests that these mechanisms functioned primarily as escalation tracking tools rather than preventive control systems. Corrective actions were frequently discussed but their frequency were moderate compared to other operational themes. This is why quality

issues often remained open across successive meetings, indicating limitations in the system's ability to eliminate root causes, and apply proper preventive measures. It also indicates that existing problems are not being closed effectively and reflects the large number of overdue issues 141 out of 142 open issues.

5.2.3 CQM as Structural Governance Backbone

The empirical findings from the study confirm that CQM constitutes the primary governance driver influencing Project Outcomes. The overall CQM mean score (3.73) reflects a moderately high level of institutional quality practices across the sampled projects. More importantly, the Structural Equation Model (SEM) demonstrated a strong and statistically significant direct effect of CQM on Project Outcomes ($\beta = 0.451$, $p < 0.001$). This result confirms that structured quality planning, quality assurance & control, and quality improvement mechanisms remain central to performance delivery.

The descriptive results indicate that quality culture and top management support recorded the highest means (above 4.10), which suggests that quality is formally recognized as a core organizational value. Quality control mechanisms also demonstrated relatively strong implementation, particularly in inspection processes and documentation systems. These findings collectively suggest that procedural and structural components of governance are firmly embedded in the projects examined.

However, the results simultaneously revealed operational imbalances within the quality system. Corrective and Preventive Action (CAPA) implementation scored the lowest mean (3.17), which indicates weakness in feedback loops effectiveness, it also reflects the reoccurring issues highlighted in JSWP quality logs. Furthermore, while spreadsheets tools showed the highest utilization (mean = 2.64) within the survey results, the enterprise-level integrated software adoption showed a low mean (2.64). This pattern of using traditional tools such as spreadsheets suggests a reliance within the selected projects on fragmented, manual tracking systems rather than integrated digital governance platforms.

The structural configuration within the projects reflects what may be described as procedural maturity without a digital integration maturity. CQM operates as a compliance-driven governance framework, but its analytical capacity remains constrained by the limited system integration and data automation. Consequently, as CQM significantly explains performance variance its influence is primarily rooted in structured discipline rather than predictive intelligence, that can support CAPA and reduce the reoccurrence of quality issues.

From a governance perspective, these findings position CQM as the foundational backbone of project control. It establishes accountability, standardization, and risk mitigation measures. However, the limitations found in digital infrastructure suggest that quality governance within JSWP projects remains largely reactive rather than fully data driven and proactive. This finding highlights a gap between current operational practices and the preventive orientation emphasized by classical quality theorists, such as Deming, Juran, and Crosby, whose frameworks advocate for systematic planning, early detection of quality issues, and continuous improvement as a fundamental principle of effective quality management.

5.2.4 AI as an Emerging Performance Enabler

5.2.4.1 Empirical Evidence of AI Performance Contribution

Artificial intelligence demonstrated a statistically significant direct effect on Project Outcomes within the SEM model ($\beta = 0.230$, $p = 0.001$), confirming AI adoption contributes independently to project performance. The overall AI mean score (3.67) indicates moderate organizational engagement with AI-related practices. Notably, interest in learning and using AI tools recorded high values from the survey results (mean=4.19). Respondents expressed strong belief in AI's potential to enhance operational efficiency and data analysis.

Despite this positive orientation, the readiness indicators present a more complex picture. The system readiness within sample projects for AI integration recorded a low to moderate mean (3.30), and enterprise software adoption remained low across projects. Additionally, qualitative responses highlighted recurring themes of

management resistance, especially in older generations, as well as cost concerns, limited infrastructure, and inadequate training.

5.2.4.2 Organizational Readiness and Digital Maturity

The descriptive results further indicate that AI utilization is currently concentrated for analytical and supportive tasks, such as data visualization, automation and document generation, rather than being embedded within core quality workflows. This level of utilization of AI technology implies that AI functions as an augmentation tool rather than a structurally integrated governance mechanism.

The coexistence of high interest and moderate infrastructure readiness reflects what may be characterized as transitional digital maturity stage. Organizations recognize the potential of AI but have not yet invested in adopting this promising technology, nor supported adoption of AI within their quality management systems. As a result, AI might improve performance directly through efficiency gains and enhanced analysis, but it does not fundamentally alter the structural dynamics of quality governance.

The interpretation is reinforced by qualitative evidence emphasizing reliance on spreadsheets, fragmented project data, and limited cross system integration between departments. Without unified digital architecture, AI applications remain promising rather than transformative and will not provide the desired cross departmental benefits and most importantly improving projects predictability and decision making.

5.2.4.3 Escalation Mechanism and Predictive Quality Intelligence

The qualitative evidence also reveals an important operational mechanism linking governance discussions to field-level quality outcomes. As discussed in early sections on the analysis of the 243 program governance documents, the results showing several repeated quality issues including contractor non-compliance, poor workmanship, inspection failures, and schedule pressure. These recurring issues were repeatedly discussed across a large number of project meetings, throughout the years, indicating that quality risks were already visible during meetings discussions long before they escalated into formal NCR or SOR.

The AI escalation model developed as part of the Quality Intelligent Dashboard provides a quantitative representation of this phenomenon. By linking 113 governance warning indicators with 673 structured quality issue records, the model demonstrates that substantial proportion of early warning subsequently escalate into documented quality events. In particular, delay- related warnings showed the highest escalation probability, highlighting the critical role of schedule pressure as a driver of quality failures. This observation is consistent with the qualitative thematic analysis of governance records, where schedule pressure appeared as the most frequently discussed issue across project meetings.

These findings suggest that meetings discussions functions as an early signal system for emerging quality risks. When projects experience schedule pressure, contractors may bypass inspections procedures, or delay corrective actions or proceed with unapproved materials, which increase the likelihood of quality escalation events. AI-Based analytical models therefore enable the transformation of these dispersed governance signals into measurable risk indicators capable of supporting proactive quality management decisions.

5.2.4.4 Quality Intelligence Dashboard Interpretation

The findings suggest that quality governance in large infrastructure program operates across three distinct decision layers: technical quality control, operational project delivery, and strategic program oversight. While each layer addresses different aspects of project performance, the absence of an integrated analytical framework limits the ability of decision-makers to identify systemic risk patterns. The proposed QIM addresses this limitation by integrating data across governance layers, enabling earlier detection of quality risks and more proactive program-level decision-making.

In addition to that, the analytical insights derived from the escalation model into practical decision-support capabilities, the developed Quality Intelligence Dashboard integrates structured issue records, escalation indicators, and contractor performance metrics. The dashboard consolidates quality data across multiple projects and visualizes key performance indicators including escalation behavior, overdue corrective actions, contractor risk rankings, and composite Quality Index.

The resulting program-level quality score indicates that JSWP currently operates within an “At Risk” quality performance category, reflecting the cumulative effect of recurring operational issues identified throughout the analysis. The dashboard therefore functions as a governance tool that transforms fragmented dispersed project data into a unified operational picture of program quality performance. By visualizing escalation patterns, contractor performance variation, and issue closure behavior, the system provides management teams with earlier visibility of emerging quality risks and supports more proactive intervention strategies.

Together, the escalation model and the Quality Intelligence dashboard demonstrate how megaproject governance can evolve using AI-enabled intelligence systems, and how it can transform governance signals and operational project data into predictive quality intelligence capable of supporting proactive quality management systems.

5.2.5 Structural Interpretation of SEM Model and Moderation Analysis

The structural Equation Modeling (SEM) analysis provided a comprehensive assessment of the relationship between CQM, AI, their interaction term, and Project Outcomes. The SEM results indicated that CQM exerts a strong and statistically significant positive effect on Project Outcomes ($\beta = 0.451$, $p < 0.001$), confirming that CQM role as a foundational governance mechanism within mega construction environment. AI also demonstrated a statistically significant direct effect on Project Outcomes ($\beta = 0.230$, $p = 0.001$), indicating that AI contributes independently to performance improvement. However, the interaction between CQM and AI was not statistically significant within the SEM framework ($\beta = 0.017$, $p = 0.448$). Accordingly, the hypothesis proposing a moderating effect of AI on the relationship between CQM and Project Outcomes was not supported in the structural model.

It is important to note that earlier, the hierarchical regression analysis suggested a statistically significant interaction effect. The divergence between the regression-based moderation result and the SEM outcome warrants methodological clarification. Hierarchical regression relies on observed composite variables and does not explicitly account for measurement error. In contrast, SEM models are latent constructs, incorporates measurement reliability, and simultaneously estimates structural paths

within an integrated framework. As a result, SEM provides a more conservative and statistically rigorous assessment of interaction effects in latent variable research. The absence of significant interaction path in the SEM model therefore represents the more robust structural conclusion.

The findings suggest that AI functions as a performance enhancer for construction projects rather than a structural amplifier for quality governance within the sampled projects. While the results showed that AI independently improves project outcomes, it does not significantly alter the strength of the relationship between CQM and Project performance. It also indicates that CQM remains the dominant governance driver, and AI operates alongside it rather than reshaping its foundational and structural influence.

Additionally, the descriptive and qualitative findings further support this interpretation. Respondents reported high awareness of AI capabilities and strong belief in its potential impact and their willingness to discover it in depth. But, organizational digital readiness or maturity indicators, such as enterprise system integration and infrastructure adequacy, were comparatively moderate to low. Moreover, qualitative responses highlighted management resistance, low interest for investments in new technologies, reliance on traditional tools, lack of enterprise platforms, and limited structural digital integration. These conditions suggest that AI adoption within the examined projects on JSWP remains at an augmentation stage rather than a transformational integration stage.

In governance terms, moderation would imply deep structural interdependence between quality management systems and digital intelligence mechanisms. The absence of statistically significant interaction effect in the SEM model indicates that such structural integration has not yet been fully realized in the projects. Instead, AI currently contributes through parallel influence by some team members as standalone initiatives, rather than been organizational wise supported through system embedded amplification.

This pattern has been reported in several projects within JSWP, and it reflects evolutionary stage of digital maturity in which technological enhanced CQM practices tools can enhance overall quality performance independently before becoming fully

integrated within governance architecture. These discovered patterns provide a subtle understanding of AI adoption in mega construction projects and lay the foundation for further theoretical advancement that will be discussed further in this chapter.

5.3 Theoretical Contributions and Advancement of Knowledge

This study contributes to the advancement of knowledge related to the intersection of Construction Quality Management, Artificial Intelligence, and project performance of mega-projects and large-scale infrastructure programs. While prior research has examined quality management frameworks and, separately, the application of AI technologies in construction, limited empirical work has investigated their integrated structural relationships within a unified analytical model. Building upon the theoretical foundations discussed in Chapter Two, namely Total Quality Management (TQM), ISO 9001, and the foundational philosophies of Deming, Juran, and Crosby. This study extends quality theory into a digitally augmented governance context. The findings not only validate core CQM principles but also provide empirical insight into the evolving maturity stage between traditional quality systems and emerging Quality 4.0 paradigms.

5.3.1 Contribution to Construction Quality Management Theory

The first theoretical contribution of this study lies in reinforcing and empirically validating CQM as a systematic governance construct rather than a collection of isolated procedural activities, that satisfies the compliance requirements. By modeling CQM as a latent variable composed of quality planning, assurance, control and improvement, the study confirms that quality management operates as an integrated governance architecture influencing overall project performance. The significant positive relationship observed between CQM, and project outcomes further supports the view that structured QMS remains a key determinant of project performance, thereby reinforcing the theoretical assumptions established by classical quality management scholars.

Deming's PDCA cycle emphasized continuous process control and systematic improvement. Juran's quality trilogy structured quality into planning, control and improvement mechanisms. Crosby's Zero Defects philosophy advocated prevention over correction. These foundational theories collectively shaped modern quality

systems, particularly ISO 9001 and TQM, as discussed in chapter two. Therefore, the empirical validation of CQM in this study confirms the following:

- Quality Planning, Control, Assurance, and Improvement operate as an integrated governance system.
- Structured quality systems remain essential in managing complexity of large-scale programs such as JSWP.
- Proactive and preventive approaches continue to influence cost, schedule, quality, and stakeholder satisfaction.

Thus, this research reinforces the enduring theoretical relevance of classical quality philosophies within contemporary mega-projects settings.

5.3.2 From TQM to Quality 4.0: Empirical Insights

The findings suggest that quality failures in megaprojects are closely linked to governance-driven schedule pressure rather than isolated technical defects. While traditional quality management systems focus on detecting defects during construction, the integration of AI-enabled analytical tools can enhance governance by identifying systemic risk patterns across operational datasets. This shift from reactive defect management to predictive risk intelligence represents a key contribution of the proposed Quality Intelligence Model.

The findings suggest that the sampled projects operate within a transitional stage of digital maturity. Classical frameworks such as TQM emphasize organizational culture, leadership commitment, and system wide responsibility. International standards such as ISO 9001 formalized these principles into documented processes, standardized procedures, and auditable management systems. However, the emergence of Industry 4.0 technologies introduces new capabilities that extend beyond procedural compliance. Technologies such as AI, predictive analytics, and digital monitoring systems enable organizations to detect patterns in operational data, anticipate risks, and support real-time decision making. But this transition toward industry 4.0 requires strong foundational governance system, as the empirical results indicate the following:

- Strong direct effect of CQM on outcomes (confirming traditional frameworks).
- Significant direct effect of AI in project performance.
- Limited moderation effect in SEM.

The empirical result of this study reflects this evolving relationship between traditional quality management and emerging digital technologies. The quantitative findings demonstrated a strong direct effect of CQM practices on project outcomes, confirming the continued relevance of established quality management frameworks. At the same time, artificial intelligence showed a statistically significant direct contribution to project performance, indicating that digital technologies can independently enhance project delivery processes. However, the moderating effect of AI within the structural equation remained limited.

This pattern suggests that AI currently functions primarily as an enhancer rather than as a fully embedded systemic moderator within construction quality governance. The findings therefore align with the emerging Quality 4.0 discourse, which conceptualize digital technologies as integrated quality enablers that extend traditional management systems rather than replacing them.

The qualitative findings further support this interpretation. Recurring governance discussions regarding schedule pressure, contractor non-compliance, and workmanship deficiencies reveal that many quality risks remain rooted in operational and organizational factors rather than technological limitations. The escalation analysis conducted in this research demonstrates that these governance signals can be transformed into measurable risk indicators through AI-supported analytical models. When combined with dashboard-based monitoring systems, these models provide managers with earlier visibility of emerging quality risks. However, the incomplete moderation observed in this study indicates that full quality 4.0 integration has not yet matured within examined context. Accordingly, this research positions large-scale infrastructure programs within a transitional evolution from procedural TQM based systems toward digitally augmented quality governance.

These observations highlight the need for structured frameworks capable of integrating traditional quality governance with emerging digital analytical capabilities. In response, this research proposes future research for the Quality Intelligence Model (QIM) as a conceptual framework for integrating artificial intelligence into Construction Quality Management systems.

5.3.3 Contribution to Artificial Intelligence Research in CQM

The second contribution addresses a critical gap in AI research within construction management. Existing studies frequently examine AI applications in specific defined technical domains, such as defect detection, computer vision monitoring, smart sensors, or drone inspections. While these studies demonstrate the technological capabilities of AI applications, they rarely position and discuss artificial intelligence within the broader governance structure of quality management systems. Although AI technologies have shown the potential to enhance CQM practices, their impact may remain below the desired level when implemented in the absence of robust quality governance frameworks capable of guiding their strategic integration.

This study adds in this regard by modelling AI as a system level construct within a structured equation framework, by examining its relationship with CQM and overall Project Outcomes. The findings confirm that AI exerts a statistically significant direct effect on project performance ($\beta = 0.230$, $p = 0.001$), thereby extending AI research beyond isolated technical applications to performance-level influence.

However, the absence of significant moderating effect in the SEM model results suggests that AI adoption within the examined context remains additive rather than structurally transformative. This distinction advances AI scholarship by differentiating between technological augmentation and systematic governance integration. It indicates that AI may enhance efficiency and analytical capacity without yet restructuring the underlying quality governance architecture.

5.3.4 Contribution to Moderation and Digital Integration Literature

Another important methodological perspective is the theoretical contribution in the empirical examination of AI as a moderating variable within construction quality governance. While hierarchical regression analysis suggested potential interaction tendencies between AI and CQM, the Structural Equation Modeling (SEM) analysis did not confirm a statistically significant moderating effect once latent constructs and measurement error were accounted for.

This methodological clarification is considered a contribution as it demonstrates the importance of using structural modeling techniques when testing moderation in complex governance systems. The divergence between regression and SEM findings underscores the necessity of cautious interpretation in digital transformation research. More importantly, the results also show that AI and CQM currently are operating in parallel rather than as structured interdependent systems. Moderation implies deep integration, feedback loops, and embedded predictive governance mechanisms. The absence of a significant interaction effect indicates that such integration has not yet been fully realized within JSWP projects.

The finding contributes to digital literature by suggesting that transformation may occur in stages, rather than structural shift. AI adoption may initially function as an independent performance enhancer before evolving toward deeper and foundational integration within governance systems. Accordingly, digital integration in Construction Quality Management may be conceptualized as a staged process consisting of Stage 0 – Traditional CQM, Stage 1 – AI-enhanced CQM, and Stage 2 – Integrated digital governance, where AI becomes structurally embedded within quality management processes. Empirical evidence suggests that the examined projects are positioned near the AI-enhanced augmentation stage, transitioning between Stage 0 and early Stage 1.

5.3.5 Contribution to Mega-project Governance in the Saudi Context

The fourth contribution relates to the contextual regional scholars. Mega infrastructure projects present governance challenges distinct from smaller construction environments due to scale, stakeholder complexity, regulatory oversights, and financial magnitude. Despite increasing global attention on digital transformation in construction, empirical evidence from large-scale projects in the Saudi context remains limited. This study provides statistically validated insights derived from high budget, multi stakeholder infrastructure program. By examining the interplay between quality governance and digital adoption in this context, the research contributes regionally grounded empirical evidence to the broader literature on construction digitalization.

Furthermore, the findings also reveal that while quality governance structures are relatively mature within these projects, digital integration remains transitional. This

nuanced understanding contributes to policy and governance discussions within rapidly developing infrastructure ecosystems, offering academically grounded evidence rather than technology driven optimism.

5.3.6 Concluding synthesis of theoretical contributions

Overall, the research findings highlight that while classical Construction Quality Management frameworks continue to provide the structural foundation for quality governance, the integration of Artificial Intelligence remains at an evolving stage. This observation underscores the need for further research into governance models capable of systematically embedding digital intelligence within quality management systems.

5.4 Practical Implications and Evidence-Based Recommendations

The empirical findings of this study provide important practical implications for governance and management practices within large-scale construction programs. The results confirmed that CQM remains the dominant structural driver of project performance, while AI contributes independently as emerging performance enhancer. However, the absence of statistically significant moderating effect indicates that AI technologies are not yet structurally embedded within quality governance mechanisms. The survey results and qualitative responses further revealed organizational challenges including limited digital infrastructure integration, reliance on spreadsheet-based tracking tools, and gaps in infrastructure and AI readiness and training for integration.

Based on these insightful findings, several evidence-based recommendations are proposed below to strengthen governance maturity and enable more effective integration of digital intelligence within QMS. The recommendations are prioritized according to governance impact, starting from executive-level interventions and progressing toward operational and technological improvements. Table (5-3) summarizes the implementation action plan derived from the empirical findings of this study and translates the proposed recommendations into structured governance and operational initiatives.

5.4.1 Establish Executive-Level Digital Quality Governance

The survey finding confirms that leadership commitments and quality culture were among the strongest dimensions of CQM. At the same time, qualitative responses show organizational hesitation toward digital transformation as well as AI integration and adoption within current systems. This is suggesting that while current quality governance structure is strong, digital integration has not yet been strategically established. Senior leaders should therefore establish executive-level digital quality governance mechanisms that formally integrate AI-supported technology into project management frameworks, including CQM, and decision-making processes. Such type of initiative will support the governance and ensure that digital transformation initiatives align with existing quality management frameworks rather than operating as isolated technological enhancers.

5.4.2 Integrate AI Analytics within Quality Monitoring Systems

The SEM results demonstrated that there is a statistically significant direct effect of AI on project outcomes, indicating that digital tools can enhance project performance through improved information processing and analytical capabilities. However, the absence of moderating effect suggests that AI tools are not yet fully embedded within the current quality governance systems. Therefore, organizations should seek to integrate AI supported analytical power into quality monitoring platforms, enabling automated analysis of inspection results, defect patterns, and performance indicators. This integration would strengthen the analytical capacity of the QMS and support more proactive decision making by management.

5.4.3 Reduce Reliance on Spreadsheet-Based Quality Tracking

Survey findings also revealed extensive reliance on spreadsheets for tracking quality-related information, while enterprise-level digital platforms such as Aconex were rarely used. Although spreadsheets offer operational flexibility, limit system integration and reduce the effectiveness of data-driven platforms that unify and organize the forms and copies of used practices. Organization should transition toward integrated digital platforms that centralize inspection logs, non-conformance reports, and quality performance metrics within unified databases. Such systems would enable real-time monitoring and improve transparency across project teams.

5.4.4 Strengthening Data-Driven Corrective and Preventive Processes

The descriptive results indicate that comparatively lower scores for corrective and preventive action (CAPA) processes compared with other CQM dimensions. It suggests that issues are detected through inspections, and systematic learning from recurring quality issues is not established. Construction organizations, especially contractors, should strengthen CAPA process through digital root-cause analysis tools that are capable of identifying and flagging recurring defect patterns and linking them to preventive strategies. Enhancing analytical feedback loops will support a shift from reactive correction of issues toward predictive quality management.

5.4.5 Develop AI Competencies Among Project Professionals

Survey responses showed strong interest among participants, especially younger generations, in learning AI tools but limited level of infrastructure readiness and formal training. This gap indicates that technology adoption must be supported by professional training and capability development. Organizations should therefore introduce structured training programs that equip quality and project teams and project managers with skills in data analytics, AI-supported reporting tools, and digital site inspection systems. At the same time, organizations must strengthen awareness of cybersecurity, data privacy, and data governance frameworks. The increasing use of AI-driven systems requires responsible management of project data, protection of digital infrastructure, and clear governance policies for data access and usage. Developing these competencies will enable quality professionals to effectively and securely utilize emerging digital technologies within their daily workflows.

5.4.6 Establish Standardized Data Architecture & Governance for Integrated Project Data

Fragmented data structures and inconsistent data gathering and reporting formats, especially using spreadsheets, were identified from responses as barriers to digital integration. Without standardized data architecture, the effectiveness of AI-supported analytics remains limited. Beyond improving quality reporting, a standardized data structure enables the integration of information across multiple projects disciplines, allowing organizations to combine data related quality, safety, schedule performance, and cost.

This cross-disciplinary integration strengthens the analytical power of digital systems by enabling the identification of relationships between site delays, safety incidents, quality issues, and their overall impact on project performance. Establishing unified data governance frameworks will therefore facilitate future digital integration and support more reliable and comprehensive performance monitoring. By enabling integrated and high-quality datasets across project disciplines, such data architecture may also enhance the potential moderating capacity of Artificial Intelligence within Construction Quality Management systems.

Table (5-3) Evidence-Based Action Plan for Enhancing AI-Integrated Construction Quality Management

No	Research Result (Chapter 4 Evidence)	Recommendation	Implementation Approach (How to Do It)	Time Frame	Required Resources	Responsible Entity	Expected Outcome / Success Indicator
1	Strong positive impact of leadership commitment and quality culture on project outcomes; qualitative responses indicate uncertainty toward AI adoption at management level.	Establish Executive-Level Digital Quality Governance to guide AI integration within quality management systems.	Form a digital quality governance committee within program leadership; incorporate AI-supported dashboards and digital performance indicators into executive quality review meetings.	6–9 months	Governance framework documentation, AI dashboards, leadership workshops	Executive Management / Program Steering Committee	Digital quality governance structure formally established and AI-based quality reports integrated into program review meetings.
2	Survey results indicate strong interest among professionals in learning AI tools but moderate levels of infrastructure readiness and training opportunities.	Develop AI competency programs for project and quality professionals.	Implement structured training initiatives covering AI tools, digital reporting platforms, and data analytics for quality engineers and project managers.	6–9 months	Training programs, digital learning platforms, external trainers or AI specialists	Human Resources / Quality / and IT Department	Increased AI literacy among project teams and improved ability to use digital tools in quality monitoring.
3	SEM results show a significant direct effect of AI on project outcomes, but no moderating integration with CQM processes.	Integrate AI analytics into quality monitoring and reporting systems.	Deploy AI-supported analytics tools to analyze inspection results, defect patterns, and quality performance indicators; embed AI insights within project performance reports.	6–12 months	AI analytics platforms, integrated reporting systems, data management tools	PMO / Quality Management Department / IT Department	AI-generated insights are incorporated into routine quality performance monitoring and reporting processes.
4	Survey findings show heavy reliance on spreadsheets for quality tracking and relatively low use of integrated enterprise software systems.	Reduce spreadsheet dependency through integrated digital quality management platforms.	Gradually migrate inspection logs, NCR tracking, and quality documentation into centralized digital platforms integrated with project management systems.	9–12 months	Enterprise software systems, system integration support, database infrastructure	IT Department / Digital Transformation Unit	Centralized digital quality tracking system operational and reduction in manual spreadsheet-based reporting processes.

No.	Research Result (Chapter 4 Evidence)	Recommendation	Implementation Approach (How to Do It)	Time Frame	Required Resources	Responsible Entity	Expected Outcome / Success Indicator
5	Lower mean scores for Corrective and Preventive Action (CAPA) processes compared with other CQM dimensions.	Strengthen data-driven CAPA mechanisms within quality management systems.	Establish centralized NCR databases and apply analytics tools to identify recurring defects, root causes, and preventive strategies.	12-16 months	NCR database systems, data analytics software, training programs	Quality Assurance and Quality Control Departments	Improved monitoring of recurring quality issues and implementation of preventive corrective action strategies.
6	Fragmented data systems and inconsistent reporting structures limit digital integration and effective AI utilization.	Establish standardized data architecture for and Governance for Integrated Project Data.	Develop unified data standards, centralized repositories for disciplines data, and integration protocols connecting inspection, reporting, and performance systems.	12–24 months	Data governance framework, IT integration tools, database infrastructure	IT Governance Team / PMO	Standardized projects data structure enabling reliable digital analytics and future AI integration.

Source: developed by the author

While the recommendations presented in this section aim to strengthen the practical integration of Artificial Intelligence within Construction Quality Management systems, they also highlight several areas that require further academic investigation. In particular, the findings of this study suggest that the digital transformation of quality governance remains an evolving process, with important questions regarding data integration, organizational readiness, and governance frameworks still requiring deeper exploration. These observations provide a foundation for identifying several directions for future research in the field of AI-enabled construction quality management.

5.5 Future Research Directions

Based on the findings, limitations, and practical implications identified in this study, several research opportunities emerge that may contribute to advancing knowledge in AI enabled CQM systems. The results of this study suggest that the integration of AI within construction quality governance may evolve through progressive strategies rather than occurring as an immediate structural transformation.

Conceptually, this evolution may be understood through three stages of digital maturity as discussed in section 5.5.6. Stage 0 represents Traditional CQM, where governance relies primarily on conventional procedural frameworks and manual reporting systems. Stage 1 reflects AI-enhanced CQM, where artificial intelligence tools support analytics, monitoring, and decision-making but remain largely external to governance structures. Step 2 represents Integrated Digital Quality Governance, where AI becomes structurally embedded within quality management processes and may exert a moderating influence on project outcomes.

The empirical evidence of this study suggests that the examined projects are currently positioned within the AI-enhanced stage of digital maturity and transitioning toward Stage one. This observation highlights several research opportunities related to digital governance, organizational readiness, and the development of integrated frameworks capable of embedding AI within QMSs.

5.5.1 Longitudinal Studies of AI integration in CQM

The present study adopted a mixed method research design, that captured the relationship between CQM and AI, and Project outcomes at a specific point of time within JSWP. However, the integration of digital technologies within construction governance systems is a dynamic process that evolves throughout the lifecycle of projects and organizations. Future research may therefore employ longitudinal research designs to examine how the integration of AI within CQM systems develops over time. Such studies could provide deeper understanding and insight into whether the moderating influence of AI becomes stronger as organizations improve digital infrastructure, data integration, and governance maturity.

5.5.2 Comparative Studies Across Project Types & Organizational Context

This research focused primarily on large-scale infrastructure projects, which typically involve complex governance structures, multiple stakeholders, and significant technological resources. Future research could extend the analysis to different types of construction projects, including residential, industrial, and smaller scale projects. Comparative studies across project types, geographic regions, and organizational structures may help determine whether the relationship among CQM, AI and project outcomes may depend on project complexity, organizational maturity, or digital readiness.

5.5.3 Cross-Disciplinary Data Integration and Project Intelligence

Another promising direction for future research involves exploring integrated data architectures capable of combining information across multiple project disciplines. While quality management data provides valuable insights, combining data related to safety, schedule delays, productivity metrics, and cost controls may significantly enhance the analytical capabilities of digital systems. Future research may therefore investigate how integrated project data ecosystems can support cross-disciplinary analytics and enable AI systems to identify complex relationships among operational variables that can influence project performance.

5.5.4 Cybersecurity, Data Privacy, Digital Governance in AI driven QMS

As construction organizations increasingly adopt digital platforms and AI-supported analytics, issues related to cybersecurity, data privacy, and digital governance become increasingly important. Future research should examine governance frameworks capable of ensuring the responsible management and protection of project data. Investigating policies for secure data sharing, ethical AI use, and digital risk management may contribute to the development of more resilient and trustworthy AI-enabled QMSs.

5.5.5 Organizational Readiness & Capability Development for AI Adoption

Survey respondents in this study indicated a strong interest from project professionals in utilizing AI tools, while infrastructure readiness and formal training levels still remained low. Future research may therefore explore organizational readiness factors that influence successful AI adoption in construction management environments. Investigating leadership commitment, workforce capabilities, digital culture, and change management strategies could provide valuable insight into how organizations can effectively transition toward AI-supported quality governance.

5.5.6 Development and Empirical Testing for the Quality Intelligence Model (QIM)

Building on the empirical insights of this study, future research may explore integrated governance frameworks that embed AI within CQM systems. One potential direction involves conceptual development and empirical testing of the QIM. The concept of this model is introduced as a potential framework for integrating AI-enabled analytics with traditional quality management processes during the early stages of project planning and implementation. During this early-stage governance structures, quality strategies, project high level objectives, and risk management strategies are initiated.

By aligning AI capabilities with core CQM functions such as quality planning and requirements, the QIM framework aims to support predictive analytics, intelligent risk detection, and data driven decision making throughout the lifecycle of the projects. Future empirical studies may test and validate the QIM framework through case studies, pilot implementation, or comparative analysis across projects with varying levels of

digital maturity in order to assess its potential contribution to the evolution of digitally augmented quality governance systems.

5.6 Limitations of the Study

While this study provides important empirical insights into the relationship between CQM, AI and Projects Outcomes, in large scale infrastructure projects, several limitations should be acknowledged when interpreting the findings.

First, the study employed a mixed method research design where data collected at a single point in time. Although this approach is common in organizational and project management research, it limits the ability to observe longitudinal changes in digital maturity and quality governance practices. The adoption and integration of artificial intelligence within CQM is an evolving phenomenon, and longitudinal studies could provide deeper understanding into how AI integration influences quantitative governance over different project phases.

Second, the research relied on survey-based responses obtained from project professionals involved in large infrastructure programs. While the sample included experienced participants from various roles and organizations, but survey data inherently dependent on respondents' perceptions and self-reported assessments of organizational practices. Also, measures were taken to ensure reliability and validity of constructs perceptual bias cannot be completely eliminated.

Third, although a total of 167 survey responses were collected, the number of responses that met the data screening criteria for statistical analysis ranged between approximately 130 and 140 valid observations. While this sample size is considered adequate for Structural Equation Modeling in management research, broader samples across multiple infrastructure programs and geographic context could enhance the generalization of the findings.

Fourth, the study focused primarily on large scale infrastructure projects in a specific regional context, Jeddah. Large scale infrastructure programs differ from smaller construction projects in governance structure, stakeholder complexity, and

technological capacity. Consequently, the findings may not be directly generalized to small and medium-sized construction environments without further empirical validation.

Finally, the study examined AI as an emerging organizational capability within CQM systems. Given the relatively early stage of AI adoption across many construction organizations, the operational maturity of digital tools varies significantly among projects. As a result, the moderating role of AI within quality governance structures may evolve as organizations continue to develop digital infrastructure and analytical capabilities.

Despite these limitations, the study provides valuable empirical evidence regarding the evolving relationship between traditional quality management frameworks and emerging digital technologies in mega construction environments.

5.7 Chapter Summary and Concluding Remarks

This chapter presented a comprehensive discussion of the empirical findings of the study and examined their implications for CQM theory, artificial intelligence adoption, and governance practices in large infrastructure projects. The analysis confirmed that CQM remains a fundamental determinant of project performance, reinforcing the continued relevance of classical quality management principles derived from TQM, ISO systems, and foundational philosophies of quality gurus.

The empirical results showed that AI also contributes positively to project outcomes, indicating that digital technologies can enhance analytical capabilities and decision support processes within construction management environments. The findings also demonstrate how artificial intelligence can augment traditional CQM practices by converting dispersed operational data into predictive quality intelligence, supporting more proactive governance in complex infrastructure projects. However, the structural analysis reveals that AI does not yet significantly moderate the relationship between CQM and Project Outcomes. These findings suggest that digital technologies are currently functioning primarily as supportive analytical tools rather than as a fully embedded governance mechanism within QMS.

This discussion of findings highlighted a transitional stage in the evolution of quality governance within infrastructure programs. While traditional quality management frameworks remain structurally strong, the integration of advanced digital technologies is still developing. This observation aligns with emerging discussions in the literature concerning the transition toward Quality 4.0, where data driven technologies, augment established quality CQM practices.

Building on these insights, the chapter presented theoretical contributions that extend existing knowledge in CQM and AI research. Practical implications were also outlined in the form of evidence-based recommendations aimed at strengthening governance structures, enhancing digital infrastructure integration, and developing organizational capabilities for AI-supported quality management.

Finally, the chapter introduced future research direction emphasizing the need to explore integrated frameworks that embed AI within QMS. In this context, the concept of the Quality Intelligence Model (QIM) was proposed as a potential research framework for examining how AI-enabled analytics can support predictive quality management and data driven decision-making in complex infrastructure projects. Further empirical investigations of such frameworks may contribute to the evolution of CQM from procedural governance toward intelligent, digitally augmented systems.

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APPENDICES



Exploring the Moderating Role of Artificial Intelligence

This questionnaire aims to understand Construction Quality Management (CQM) practices and changes, as well as the potential for utilizing artificial intelligence (AI) tools effectively to enhance various aspects of project quality management and their impact on project outcomes.

Your insights will help us identify current challenges and potential solutions for integrating AI in this crucial domain.

By: Eng. Ismail Hasan Ujaimi

PhD Candidate in Quality Management at Midocean University

Part A: Project Management Background & Experience

1. What is your role in the company?

- ☐ Director or Higher
- ☐ Senior Manager
- ☐ Manager
- ☐ Senior Engineer
- ☐ Engineer
- ☐ Inspector

* 2. What is your department?

- ☐ Management
- ☐ Construction
- ☐ Quality
- ☐ HSE
- ☐ Planing / Cost control
- ☐ Technical
- ☐ Other

* 3. What is the role of your organization in the project?

- ☐ Client
- ☐ PMO / PMC
- ☐ Supervision Consultant
- ☐ Contractor / Sub-Contractor
- ☐ Supplier

* 4. How many years of experience do you have?

- ☐ 0 - 5 Years
- ☐ 6 - 10 Years
- ☐ 11 - 15 Years
- ☐ 16 - 20 Years
- ☐ More than 20 years

* 5. What is your highest level of Education?

- ☐ PhD
- ☐ Masters
- ☐ Bachelor
- ☐ Diploma

* 6. What is the scale of the project based on the budget?
(based on MOMRA classification)

- ☐ Small < SR 50 million
- ☐ Meduim SR 50 - 200 million
- ☐ Big > SR 200 million

* 7. What is the scale and complexity of the project team

- ☐ Small team (Less than 50 members)
- ☐ Meduim team (50-150 members)
- ☐ Large team (150+ members)
- ☐ Large multinational team (150+ members)

8. Did you acquire any of the following certificates? (chose all that applies)

- ☐ PMP
- ☐ RMP
- ☐ Prince
- ☐ ISO Lead Auditor
- ☐ Lean Six Sigma
- ☐ Certified Manager of Quality
- ☐ Other (please specify)

9. If working on the Jeddah stormwater program please include the project name for analysis purposes?

* 10. What is your gender?

- ☐ Male
- ☐ Female



Exploring the Moderating Role of Artificial Intelligence

Part B1: Construction Quality Management “CQM” Practices Background:

Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 11. Construction Quality Management “CQM” Practices Background

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality is considered a core value within my organization and supported by higher management	☐	☐	☐	☐	☐
Organizations’ Quality cultural patterns, like rituals, beliefs, values, and everyday procedures, directly or indirectly affect CQM practice?	☐	☐	☐	☐	☐
ISO 9001 certification among stakeholders positively contributes to orngasational and projects sucess	☐	☐	☐	☐	☐

* 12. We are facing the following challenges in maintaining quality across the current projects?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Difficulty in identifying quality defects at early stages	☐	☐	☐	☐	☐
Challenges in managing and tracking defect resolution	☐	☐	☐	☐	☐
Difficulty ensuring compliance with standards/specifications	☐	☐	☐	☐	☐
Ineffectiveness in implementing corrective actions	☐	☐	☐	☐	☐
Lack of structured preventive action mechanisms	☐	☐	☐	☐	☐
Gaps in workforce skill level and training	☐	☐	☐	☐	☐
Absence of standardized quality strategies or best practices	☐	☐	☐	☐	☐

* 13. How frequently do you use the following tools or techniques for quality monitoring and analysis in your current project? Please rate based on your current project experience

	Not used	Rarely used	Sometimes used	Frequently used	Always used
Spreadsheets (e.g., Excel)	☐	☐	☐	☐	☐
KPIs Dashboards (Power BI / Tableau)	☐	☐	☐	☐	☐
Generic project software (e.g., MS Project, Primavera)	☐	☐	☐	☐	☐
Document-sharing platforms (e.g., SharePoint, Cloud storage, Google drive, Dropbox)	☐	☐	☐	☐	☐
Enterprise software (e.g., Oracle Unifier, Procore, Aconex)	☐	☐	☐	☐	☐

14. Which tool of the above mentioned do you find most effective, and why?

15. Please describe any specific challenges faced in implementing or improving quality practices?



Exploring the Moderating Role of Artificial Intelligence

Part B2: Dimensions of Construction Quality Management practices (Quality Planing - Quality Assurance - Quality Control - Quality Improvement)
Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 16. To what extent do you agree with the following statements related to **Quality Planning** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
There is a formal Quality Management System with clear Quality objectives, policy, procedures, and KPIs within the organization	☐	☐	☐	☐	☐
Project Quality Plans are prepared during the planning stage for each project	☐	☐	☐	☐	☐
We use defined quality objectives, performance indicators, and checklists	☐	☐	☐	☐	☐
Stakeholders are involved in the process of quality planning.	☐	☐	☐	☐	☐
Lessons learned from previous / similar projects are used	☐	☐	☐	☐	☐
Risk-based thinking is applied during quality planning to anticipate potential quality issues	☐	☐	☐	☐	☐
Quality planning includes clear roles, responsibilities, and communication plans	☐	☐	☐	☐	☐

* 17. To what extent do you agree with the following statements related to **Quality Assurance** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality audits are conducted regularly and effectively	☐	☐	☐	☐	☐
Management review meetings are conducted regularly and effectively	☐	☐	☐	☐	☐
Audit results are documented, communicated, and followed up with corrective or preventive actions	☐	☐	☐	☐	☐
There are procedures to evaluate and control the quality performance of contractors, subcontractors, and suppliers	☐	☐	☐	☐	☐
There are clear internal communication processes for enforcing quality standards	☐	☐	☐	☐	☐
Top management demonstrates strong commitment to quality assurance	☐	☐	☐	☐	☐

* 18. To what extent do you agree with the following statements related to **Quality Control** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
There are a flow chart and procedures showing the process of quality control such as inspections, NCRs, SORs.	☐	☐	☐	☐	☐
Regular inspections and testing procedures are followed as per ITP	☐	☐	☐	☐	☐
Non-conformities are identified and corrected in a timely manner	☐	☐	☐	☐	☐
Documentation systems (e.g., NCR logs, SORs, issue logs) are consistently used to track quality issues	☐	☐	☐	☐	☐
Inspection and test results are reviewed and analyzed to identify trends and recurring issues	☐	☐	☐	☐	☐
Coordination occurs between site engineers, QA/QC staff, and contractors to resolve quality issues	☐	☐	☐	☐	☐

* 19. To what extent do you agree with the following statements related to **Quality Improvement** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality procedures are reviewed and updated regularly	☐	☐	☐	☐	☐
There are effective mechanisms for capturing feedback and lessons learned	☐	☐	☐	☐	☐
Training programs on quality standards are provided continuously	☐	☐	☐	☐	☐
Corrective and preventive actions (CAPA) are actively implemented and monitored	☐	☐	☐	☐	☐
Quality performance data is analyzed periodically to identify improvement opportunities	☐	☐	☐	☐	☐

Exploring the Moderating Role of Artificial Intelligence

Part C: Project Outcomes (Time-Cost-Quality-Customer satisfaction) and Perceived Impact of CQM Practices

Please indicate your level of agreement with the following statements regarding how current quality management practices have influenced project outcomes (1 = Strongly Disagree, 5 = Strongly Agree)

* 20. To what extent do you agree with the following statements related to the impact of Quality Management practices on **project cost** in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality practices help in controlling project cost overruns by reducing reworks	☐	☐	☐	☐	☐
Rework due to quality issues increases project costs	☐	☐	☐	☐	☐
Cost-related risks due to poor quality are identified and mitigated proactively	☐	☐	☐	☐	☐
The organization tracks and reports both direct quality costs and indirect costs related to quality	☐	☐	☐	☐	☐

* 21. To what extent do you agree with the following statements related to the impact of Construction Quality Management practices on **project schedule**?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
The presence of robust CQM practices can reduce the frequency of rework and schedule overruns	☐	☐	☐	☐	☐
Quality-related delays (e.g., material rejection, repair, rework) are concerning in our project	☐	☐	☐	☐	☐
Early detection and resolution of quality issues contributes to avoiding negative schedule disruptions	☐	☐	☐	☐	☐

* 22. To what extent do you agree with the following statements related to the impact of Construction Quality Management practices on **overall project quality**?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Robust CQM practices help in improving the overall quality of works	☐	☐	☐	☐	☐
Few defects are observed during project handover and included in the snag list	☐	☐	☐	☐	☐
Project outputs comply with specifications and quality standards	☐	☐	☐	☐	☐
Post-handover claims due to quality defects are minimal, as issues are addressed before final project handing over	☐	☐	☐	☐	☐

* 23. To what extent do you agree with the following statements related to **customer satisfaction** in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
CQM practices help to improve the overall quality of work, therefore increasing customer satisfaction	☐	☐	☐	☐	☐
Clients or end users express satisfaction with delivered quality	☐	☐	☐	☐	☐
Quality management improves stakeholder communication and satisfaction	☐	☐	☐	☐	☐
Customer feedback is regularly collected and used to improve project delivery and quality performance	☐	☐	☐	☐	☐



Exploring the Moderating Role of Artificial Intelligence

Part D: Potential AI Applications in Construction Quality Management Practices

Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 24. To what extent do you agree with the following statements related to your **awareness and readiness** to adopt AI technologies in construction project quality management?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
I am interested in learning and using (AI) to enhance practices in my organization, including quality management	☐	☐	☐	☐	☐
I personally use AI tools such as ChatGPT and similars, to improve my productivity	☐	☐	☐	☐	☐
I am familiar with AI technologies (e.g., ML, NLP, computer vision, IoT)	☐	☐	☐	☐	☐
There are initiatives in Our organization to integrate AI in project process including quality	☐	☐	☐	☐	☐
Special training on using AI tools is needed for our staff	☐	☐	☐	☐	☐
Staff are competent and open to using AI tools in quality management	☐	☐	☐	☐	☐
The current system in your organization is ready to be integrated with AI technology	☐	☐	☐	☐	☐
The integration of AI can positively influence the project's outcomes and overall success	☐	☐	☐	☐	☐

* 25. To what extent do you agree with the following statements about how AI can be utilized throughout the quality lifecycle in construction projects?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
AI tools can be used for generating quality requirements from historical data	☐	☐	☐	☐	☐
AI Could help automating operations and digitalizing processes to improve productivity, safety, and quality	☐	☐	☐	☐	☐
AI Integration can help analyze quality data and identify trends and patterns	☐	☐	☐	☐	☐
AI Could help improve communication and collaboration between stakeholders on quality issues	☐	☐	☐	☐	☐
AI supports compliance checking with codes, standards, and projects specifications	☐	☐	☐	☐	☐
AI-powered dashboards are used for predictive insights during project execution	☐	☐	☐	☐	☐
AI tools help in detecting errors or defects earlier than traditional methods, especially if integrated with dashboards	☐	☐	☐	☐	☐
AI Integration help to predict and prevent errors related to humans, observations, non-conformities, before they occur	☐	☐	☐	☐	☐

* 26. To what extent do you agree with the following statements regarding the adoption of Artificial Intelligence (AI) in your organization and specifically within your Construction Quality Management (CQM) practices?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Our organization’s top management is committed to exploring and supporting the use of AI	☐	☐	☐	☐	☐
There is strong organizational interest in applying AI in all processes including quality	☐	☐	☐	☐	☐
Implementation cost is a major concern that limits the adoption of AI	☐	☐	☐	☐	☐
Our current systems and tools can be integrated with AI with minimal adjustments	☐	☐	☐	☐	☐
There is a lack of internal AI-related training programs for staff	☐	☐	☐	☐	☐
We face challenges in collecting and organizing quality-related data that AI systems can use	☐	☐	☐	☐	☐
There are concerns about the accuracy and reliability of AI-generated quality insights	☐	☐	☐	☐	☐
Our organization sees AI as a future enabler for improving overall project delivery	☐	☐	☐	☐	☐
Current CQM workflow can be integrated with AI for better predictive control	☐	☐	☐	☐	☐
We are actively exploring partnerships or solutions to enhance AI capabilities	☐	☐	☐	☐	☐
Transparency, bias, reliability, accountability, ethical and legal considerations are biggest concerns for using AI	☐	☐	☐	☐	☐

27. What recommendations would you give for developing and implementing AI solutions for CQM effectively?

28. Please share any observations, insights, thoughts or experiences where AI improved or could have improved project outcomes?

Qualitative Thematic Analysis of JSWP Minutes of Meetings and Progress Reports

Convergent Mixed-Methods Triangulation — Thesis Chapter Support Document

Revised Edition — Full Corpus (243 Documents)

Program: Jeddah Stormwater Program (JSWP) **Analysis Scope:** 73 WSP QAQC Meeting Minutes + 169 Client Progress Meeting Minutes + 1 Survey Results Document **Total Documents Analysed:** 243 **Total Source Text Processed:** ~1.2 million characters **Total Quality-Related Statements Coded:** 11,090 **Analysis Date:** March 2026

Revision Note

This report supersedes the initial analysis (51 documents, 339 coded statements). The first pass covered only the WSP QAQC project-level meeting minutes. Upon verification, two additional document collections were identified and incorporated:

Collection	Documents	Period	Language	Previously Included
WSP Projects QAQC MOMs	73	Mar 2025 – Oct 2025	English	Partial (51 of 73)
Client Progress Meeting Minutes	169	Jan 2021 – Oct 2025	Arabic	None
Survey Results	1	2025	English	Yes
Total	243	2021–2025	Mixed	—

The Client Progress Meeting Minutes represent weekly programme-level meetings chaired by the client (PMO), covering all JSWP projects collectively. Their inclusion provides a five-year longitudinal view of quality management challenges at the programme governance level — a perspective entirely absent from the initial analysis.

Executive Summary

This report presents a five-step qualitative thematic analysis of the complete JSWP documentation corpus, conducted to support a Convergent Mixed-Methods research design for thesis research. Across 243 documents and 11,090 coded statements, ten distinct quality themes were identified. The analysis reveals that quality challenges in JSWP are not only widespread at the project execution level (as shown by the WSP QAQC MOMs) but are also deeply embedded in the programme’s governance and delivery culture, as evidenced by the five-year longitudinal record in the Client Progress Meeting Minutes.

The central finding is one of **strong convergence** between the qualitative evidence and the quantitative AI Risk Model outputs. The top three qualitative themes — Progress & Schedule Issues (n=3,176), Poor Workmanship (n=1,565), and Contractor Non-Compliance (n=1,354) — map directly to the three highest-impact predictors in the AI escalation model. Critically, the Client MOMs reveal that these problems have been present and discussed at the programme level since at least 2021, predating the current QAQC monitoring framework. This longitudinal persistence is a key finding for the thesis: the AI model is not detecting new problems but quantifying the risk profile of long-standing, structurally embedded quality challenges.

Step 1 — Document Corpus and Extraction Methodology

Corpus Overview

Collection	Documents	Coded Statements	% of Total Statements
Client Progress Meeting Minutes (Arabic)	169	9,267	83.6%
WSP QAQC Meeting Minutes (English)	73	1,645	14.8%
Survey Results (English)	1	178	1.6%
Total	243	11,090	100%

Extraction Methodology

Text was extracted from all 243 Word-format documents (.docx and .docm) using XML-level parsing of the Office Open XML structure, bypassing macro-enabled format restrictions. For Arabic documents, the full Unicode text was preserved and coded against a bilingual keyword vocabulary (Arabic and English). Sentences were segmented on punctuation boundaries and table-row delimiters, filtered to 20–600 characters, and tested against a 130-keyword thematic coding vocabulary distributed across ten themes.

Project Coverage

Project	WSP MOM Documents	Client MOM Documents	Total
Al-Hamrah	16	—	16
Hail	21	—	21
Al-Huda	17	—	17
Al-Rawdah	2	—	2
North Channel	2	—	2
Al-Marwah	3	—	3
Al-Falah	2	—	2
South Obhur	3	—	3
King Faisal Road	1	—	1
Al-Abruq	4	—	4
Programme-Wide	2	169	171
Total	73	169	242

Step 2 — Thematic Coding

Methodology

Each extracted statement was tested against a bilingual (Arabic/English) vocabulary of 130 keyword patterns across ten themes. Themes were derived from the established Construction Quality Management literature and calibrated to the JSWP operational context. A statement could be assigned to multiple themes.

Thematic Frequency Table — Full Corpus

Rank	Theme	Frequency	Documents	% of Docs	Prevalence
1	Progress & Schedule Issues	3,176	201	83%	Very High
2	Poor Workmanship	1,565	231	95%	Very High
3	Contractor Non-Compliance	1,354	227	93%	Very High
4	Safety & Environmental	1,330	195	80%	Very High
5	Inspection Failures	1,257	225	93%	Very High
6	Coordination Problems	1,207	206	85%	Very High
7	Delayed Corrective Actions	465	221	91%	High
8	Resource Constraints	412	131	54%	Moderate
9	Management Escalations	248	112	46%	Moderate
10	Material Approval Delays	76	68	28%	Low
Total		11,090	—	—	—

Critical observation: Six of the ten themes appear in more than 80% of all 243 documents. This near-universal prevalence is not characteristic of isolated or project-specific problems — it is the signature of systemic, programme-wide quality management failures that have persisted across a five-year period and across all JSWP projects.

Comparison: Initial vs. Full Corpus Analysis

The inclusion of the Client MOMs fundamentally changes the frequency ranking and reveals the programme-level perspective:

Theme	Initial (51 docs)	Full Corpus (243 docs)	Change	New Insight
Contractor Non-Compliance	106 (Rank 1)	1,354 (Rank 3)	+1,248	Still dominant at project level; surpassed by schedule/workmanship at programme level
Poor Workmanship	61 (Rank 2)	1,565 (Rank 2)	+1,504	Most pervasive theme across all document types
Progress & Schedule Issues	Not coded	3,176 (Rank 1)	New	Client MOMs reveal schedule pressure as the dominant programme-level concern
Material Approval Delays	52 (Rank 3)	76 (Rank 10)	+24	Less prominent at programme level; concentrated in project-level QAQC discussions
Safety & Environmental	Not coded	1,330 (Rank 4)	New	Client MOMs include HSE reporting absent from QAQC MOMs

Representative Statements by Theme

Progress & Schedule Issues (n=3,176, 201 documents)

The dominance of this theme in the Client MOMs reflects the PMO's primary concern with programme delivery milestones. Arabic-language discussions consistently reference project completion percentages, delayed handovers, and contractor schedule non-compliance. English QAQC MOMs add the quality dimension: schedule pressure from contractors leads to shortcuts in inspection compliance and material approval processes.

- *Al-Hamrah, Oct 2025*: "WSP ask for updated schedule for follow-up. CWC will provide a schedule for the status of the cover for PRD and MH."
- *Client MOM, 2024 (Arabic)*: Programme-level discussion of project completion percentages and delayed milestones across multiple JSWP packages.
- *Hail, Apr 2025*: "A meeting is to be arranged with WSP team regarding PMO's NCR & SOR closure process on Monday 27/04/2025 at 2:30 PM."

Poor Workmanship (n=1,565, 231 documents — 95% coverage)

This theme's appearance in 95% of all documents makes it the single most pervasive quality issue in the programme. It spans both the project-level QAQC discussions (specific defects in asphalt, compaction, concrete, and pipe installation) and the programme-level client meetings (general references to quality standards and rectification requirements).

- *Al-Hamrah, Aug 2025*: "Implementation Quality of asphalt works on Line AH01-5-1 PRD. CWC started cutting asphalt for rectification as per WSP road Engineer instruction."
- *Al-Huda*: "Works Methodologies statement approvals & logs. Concrete Mixed design approvals & logs. Independent third-party lab or Site lab testing materials — approvals."
- *Al-Hamrah, Jun 2025*: "Rectification work has been started for the storage area. CWC. 1/7/2025. Open."

Contractor Non-Compliance (n=1,354, 227 documents — 93% coverage)

Present in 93% of all documents, this theme confirms that contractor non-compliance is not a project-specific aberration but a programme-wide behavioural pattern. The QAQC MOMs provide specific evidence (repeated "Continues Action" items, NCR/SOR log follow-up), while the Client MOMs show that the PMO has been aware of and discussing contractor compliance issues since 2021.

- *Al-Hamrah, Mar 2025*: "CWC shall rectify or replace Stockpile area sieves mesh and repeated violation."
- *Al-Hamrah, Mar 2025*: "CWC shall use approved capacity Roller equipment for compaction Earth works. CWC Continues Action."
- *North Channel, Apr 2025*: "SAJCO provided the work inspection request to the quality team in WSP in order to close out SOR."

Inspection Failures (n=1,257, 225 documents — 93% coverage)

The near-identical document coverage of Contractor Non-Compliance and Inspection Failures (both 93%) suggests these two themes are structurally linked: contractor non-compliance manifests most frequently as inspection failures, and inspection failures are the primary mechanism by which SORs escalate to NCRs.

- *Al-Hamrah, Mar 2025*: "CWC provided the work inspection request for MH 19 in Line Ah01 and MH 21, MH20, MH 19 Line AH07 to the quality team in WSP in order

to close out SOR 224 and SOR 225.”

- *Al-Falah, Apr 2025*: “GRP for ⁵⁰⁰/₃₀₀ Dia shall be tested as per the approved ITP. UPVC 400 Dia Ground water line shall be arranged mandrel test as per project specs.”
- *Al-Rawdah, Mar 2025*: “The contractor must issue WIR with full coordination with the consultant before any construction step.”

Delayed Corrective Actions (n=465, 221 documents — 91% coverage)

Despite its lower frequency relative to the top themes, Delayed Corrective Actions appears in 91% of all documents — the third-highest document coverage of any theme. This indicates that while individual instances are less frequent, the problem of unclosed corrective actions is nearly universal across the programme.

- *Al-Hamrah, Mar 2025*: “The LOG for NCR/SOR should be available during weekly meeting to discuss and follow up for closeout.”
- *Al-Hamrah, Mar 2025*: “QC Statistics: Total Closed Open — SORs 14, 7, 7; NCRs 14, 7, 7.”
- *Al-Abruq*: Multiple consecutive MOMs showing the same action items carried forward as “Open.”

Material Approval Delays (n=76, 68 documents — 28% coverage)

The relatively low frequency of this theme in the full corpus (compared to its prominence in the initial QAQC-only analysis) reveals an important distinction: material approval is primarily a project-level quality management concern discussed in QAQC meetings, not a programme-level governance concern discussed in client progress meetings. This does not diminish its importance — the AI model identifies it as the highest-escalation technical warning type (58.3%) — but it explains why it is less visible at the PMO level.

Step 3 — Theme-to-Issue Mapping

Mapping Table

Qualitative Theme	Related Issue Category	AI Warning Type	Escalation Rate	Domain	Alignment
Progress & Schedule Issues	Overdue Issues / Delay	Delay	66.7%	D-QMS	Strong
Poor Workmanship	General Quality	General Quality	47.7%	D-RST	Strong
Contractor Non-Compliance	High Contractor Risk	Coordination Issue	33–72%	D-QMS	Strong
Safety & Environmental	General Quality	General Quality	47.7%	D-HSE	Moderate
Inspection Failures	Inspection Failure	Inspection Failure	49.0%	D-QMS	Strong
Coordination Problems	Coordination Issue	Coordination Issue	33.3%	D-CON	Moderate
Delayed Corrective Actions	Overdue Issues	Delay	66.7%	D-QMS	Strong
Resource Constraints	General Quality	General Quality	47.7%	D-QMS	Moderate
Management Escalations	High Escalation Risk	Delay	66.7%	D-QMS	Moderate
Material Approval Delays	Material Risk	Material Risk	58.3%	D-MAT	Strong

Key Mapping Insights

The mapping reveals two structural patterns that are critical for the thesis argument. First, the three highest-frequency qualitative themes (Progress & Schedule Issues, Poor Workmanship, Contractor Non-Compliance) all map to warning types with

escalation rates above 47% — confirming that the issues most discussed in meetings are also the issues most likely to escalate into formal non-conformances. Second, the theme with the lowest qualitative frequency (Material Approval Delays, n=76) maps to the warning type with the highest technical escalation rate (58.3%), suggesting that while material approval issues are discussed less frequently in meetings, they are disproportionately dangerous when they do occur.

Survey Corroboration

The survey results (n=167 respondents, Cronbach's $\alpha=0.949$) provide additional bridging evidence across the theme-to-issue mapping:

Survey CQM Dimension	Mean Score	%	Relevance to Thematic Mapping
AI Utilization	3.93	78.6%	Supports thesis argument for AI-based QI Model
Quality Control	3.88	77.6%	High score yet widespread inspection failures — execution gap
Quality Planning	3.82	76.4%	Plans exist but not followed — contractor non-compliance
Quality Assurance	3.76	75.2%	Audit findings unclosed — audit-escalation linkage
Quality Improvement	3.61	72.2%	Lowest score — confirms corrective action system failure

The survey's finding that Quality Improvement is the weakest CQM dimension (Mean=3.61) is the most significant corroborating data point: it directly confirms the qualitative evidence that corrective actions are not being effectively closed and that recurring issues are not being systematically eliminated.

Step 4 — Triangulation Analysis

Triangulation Table — Full Corpus

Quantitative Finding	Qualitative Evidence	Interpretation
Delay warnings: highest escalation rate (66.7%)	Progress & Schedule Issues is the most frequent theme (n=3,176, 83% of docs). Client MOMs show 5 years of schedule pressure discussions.	Schedule pressure is the primary programme-level driver of quality risk. When contractors are behind schedule, they bypass inspection and approval requirements, directly triggering the escalation pathway.
Poor Workmanship: 47.7% escalation rate; widespread in NCRs	Poor Workmanship is the most pervasive theme (n=1,565, 95% of docs). Appears in virtually every document across all projects and years.	Workmanship quality is a chronic, programme-wide failure. Its near-universal document coverage (95%) confirms this is not a contractor-specific or project-specific problem but a systemic delivery quality issue.
Contractor risk: dominant predictor (impact score 92); high-risk contractors escalate 3× more	Contractor Non-Compliance appears in 93% of all documents (n=1,354). Client MOMs show this has been discussed at PMO level since 2021.	Contractor behaviour is the root cause of the majority of escalations. The 5-year longitudinal evidence from Client MOMs confirms this is a structural, not incidental, programme risk. The AI model is quantifying a problem that has been visible in meeting records for years.
Inspection Failure: 7-day escalation window	Inspection Failures appears in 93% of documents (n=1,257). QAQC MOMs show WIR non-compliance as a recurring pattern.	The 7-day escalation window is a procedural consequence of inspection non-compliance. The near-identical document coverage of Contractor Non-Compliance and Inspection Failures (both 93%) confirms these are two manifestations of the same underlying behavioural problem.
Material Risk: 58.3% escalation rate	Material Approval Delays appears in 28% of documents (n=76) —	Material approval failures are a project-level technical risk, not a programme-level governance concern. Their low visibility in

Quantitative Finding	Qualitative Evidence	Interpretation
(highest technical rate)	concentrated in QAQC MOMs, not Client MOMs.	Client MOMs explains why they may be under-managed at the PMO level despite carrying the highest technical escalation rate. This is a key thesis finding: the PMO's governance view and the QAQC operational view diverge most sharply on material risk.
85% of warnings are in projects with overdue audit findings	Delayed Corrective Actions appears in 91% of documents (n=465). Audit findings from July 2025 remain 100% open.	Audit closure requires the same corrective actions that are themselves overdue. The 91% document coverage of Delayed Corrective Actions confirms that the corrective action system failure is programme-wide, explaining why audit findings cannot be closed.
Program QI = $\frac{45}{100}$ (At Risk); escalation rate = 49.6%	Management Escalations (n=248, 46% of docs). Survey: Quality Improvement lowest CQM dimension ($3.\frac{61}{5.00}$).	The low Program QI reflects the cumulative effect of all qualitative themes operating simultaneously across the programme. The survey confirms that the programme lacks effective improvement mechanisms — it manages quality reactively rather than proactively.
Coordination Issue: lowest escalation rate (33.3%)	Coordination Problems appears in 85% of documents (n=1,207) but with lower severity per instance.	The high document coverage but low escalation rate for coordination issues confirms that coordination problems are being identified and discussed in meetings before they reach formal NCR status. The MOM format is effective at containing coordination issues — its least effective function is closing corrective actions.

Step 5 — Narrative Insight Summary

The Five-Year Longitudinal View: What the Client MOMs Reveal

The most significant finding from the full corpus analysis is that the quality challenges currently being detected by the AI Risk Model are not new. The Client Progress Meeting Minutes — 169 weekly Arabic-language meetings spanning January 2021 to October 2025 — show that Poor Workmanship, Contractor Non-Compliance, and Progress & Schedule Issues have been recurring discussion items at the PMO level throughout the programme's lifecycle. This longitudinal evidence transforms the thesis argument: the AI model is not predicting novel risks but is providing a systematic, quantified framework for risks that have been visible in meeting records for years without being effectively resolved.

This finding has profound implications for the thesis's contribution. It demonstrates that the problem is not a lack of information — the PMO has been receiving weekly reports on these issues for five years — but a lack of a structured analytical framework to translate that information into predictive risk intelligence. The Quality Intelligence Model addresses precisely this gap.

How MOM Discussions Support the AI Model Results

The Schedule-Quality Nexus. The dominance of Progress & Schedule Issues (n=3,176, 83% of documents) in the full corpus reveals a mechanism not visible in the QAQC-only analysis: schedule pressure is the primary driver of quality shortcuts. When contractors are behind schedule — as evidenced by five years of PMO-level schedule discussions — they bypass inspection requirements, proceed with unapproved materials, and delay corrective actions. The AI model captures the downstream consequences of this behaviour (inspection failures, material risk warnings, delay escalations), while the Client MOMs document the upstream cause (persistent schedule non-compliance). Together, they establish a causal chain from schedule pressure to quality escalation.

The Workmanship-Escalation Pathway. Poor Workmanship's appearance in 95% of all documents — the highest document coverage of any theme — establishes it as the most pervasive quality failure in the programme. The QAQC MOMs provide specific evidence of defects (asphalt rectification, compaction failures, concrete mix non-compliance), while the Client MOMs show that workmanship quality has been a

standing agenda item at the PMO level throughout the programme. The AI model's General Quality warning type (47.7% escalation rate) captures this theme quantitatively, but the qualitative evidence reveals that workmanship failures are the visible manifestation of deeper systemic issues: inadequate contractor supervision, insufficient quality control resources, and the absence of effective quality improvement mechanisms.

The Contractor Behaviour Pattern. Contractor Non-Compliance in 93% of documents over five years establishes a clear behavioural pattern: the contractors engaged in JSWP have consistently failed to comply with quality requirements across multiple projects, multiple years, and multiple contract packages. The AI model's identification of contractor performance as the dominant escalation predictor (impact score 92, $3\times$ escalation multiplier for high-risk contractors) is not a statistical artefact — it is the quantification of a behavioural pattern that has been documented in meeting records since 2021. The qualitative evidence from Client MOMs confirms that this pattern was known at the PMO level but not effectively addressed through the existing quality management framework.

The Corrective Action System Failure. Delayed Corrective Actions appears in 91% of all documents — the third-highest document coverage. This near-universal presence, combined with the survey's finding that Quality Improvement is the weakest CQM dimension ($3.61/5.00$), confirms a structural failure in the programme's corrective action system. Items are identified, documented, and discussed in meetings, but they are not being effectively closed. The AI model captures this as the highest-escalation warning type (Delay, 66.7%), confirming that the failure to close corrective actions is not merely an administrative inconvenience but the single highest-risk pathway to formal NCR escalation.

The PMO-QAQC Perception Gap. A key finding that emerges from comparing the two document collections is a significant divergence in what is visible at the PMO level versus the QAQC operational level. Material Approval Delays — the highest-escalation technical warning type (58.3%) — appears in only 28% of documents and is concentrated in QAQC MOMs, not Client MOMs. This means that the PMO's weekly governance meetings are not surfacing the issue that the AI model identifies as the most dangerous technical risk. Conversely, Progress & Schedule Issues — the dominant theme in Client MOMs — is not a formal warning type in the AI model, suggesting that the model is capturing the downstream quality consequences of schedule pressure without explicitly modelling the schedule pressure itself. These

gaps represent opportunities for the Quality Intelligence Model to bridge the PMO-QAQC information divide.

Key Recurring Operational Problems

Based on the integrated analysis of 243 documents across five years, five structural quality problems emerge as the primary drivers of programme risk:

1. Chronic Schedule Non-Compliance Driving Quality Shortcuts. The five-year record of schedule discussions in Client MOMs, combined with the AI model's identification of Delay warnings as the highest-escalation type (66.7%), establishes schedule pressure as the root cause of the majority of quality failures. Contractors behind schedule bypass quality requirements, creating a cascade of inspection failures, material approval shortcuts, and delayed corrective actions.

2. Systemic Workmanship Deficiencies Across All Projects. Poor Workmanship's 95% document coverage over five years indicates that workmanship quality is a programme-wide structural failure, not a contractor-specific or project-specific problem. This suggests that the root cause lies in programme-level factors: contractor selection criteria, supervision intensity, quality control resourcing, and the absence of effective quality improvement mechanisms.

3. Persistent Contractor Non-Compliance Without Effective Consequences. Contractor Non-Compliance in 93% of documents over five years, with the same contractors (CWC, SAJCO) repeatedly cited, indicates that the current corrective action framework is insufficient to change contractor behaviour. The AI model's 3× escalation multiplier for high-risk contractors quantifies the cost of this failure.

4. Corrective Action System Failure at All Levels. The 91% document coverage of Delayed Corrective Actions, combined with 100% open audit findings (8+ months overdue), confirms that the programme's corrective action system is not functioning at any level — project, programme, or audit. This is the single most actionable finding for the PMO: the quality management system has the right structure but lacks the enforcement mechanisms to drive closure.

5. PMO-QAQC Information Divide. The divergence between what is discussed in Client MOMs (schedule, workmanship, contractor behaviour) and what is tracked in QAQC MOMs (material approvals, inspection compliance, NCR/SOR closure) represents a structural information gap. The PMO is managing quality at the governance level

without full visibility of the technical risk signals that the AI model identifies as the highest-escalation indicators. The Quality Intelligence Model addresses this gap by providing a unified analytical framework that integrates both perspectives.

Summary of Deliverables

Deliverable 1: Thematic Frequency Table — Full Corpus

Rank	Theme	Frequency	Documents	% of Docs
1	Progress & Schedule Issues	3,176	201	83%
2	Poor Workmanship	1,565	231	95%
3	Contractor Non-Compliance	1,354	227	93%
4	Safety & Environmental	1,330	195	80%
5	Inspection Failures	1,257	225	93%
6	Coordination Problems	1,207	206	85%
7	Delayed Corrective Actions	465	221	91%
8	Resource Constraints	412	131	54%
9	Management Escalations	248	112	46%
10	Material Approval Delays	76	68	28%

Deliverable 2: Theme-to-Issue Mapping

Theme	Issue Category	Warning Type	Escalation Rate	Alignment
Progress & Schedule Issues	Overdue Issues	Delay	66.7%	Strong
Poor Workmanship	General Quality	General Quality	47.7%	Strong
Contractor Non-Compliance	High Contractor Risk	Coordination Issue	33–72%	Strong
Inspection Failures	Inspection Failure	Inspection Failure	49.0%	Strong
Delayed Corrective Actions	Overdue Issues	Delay	66.7%	Strong
Material Approval Delays	Material Risk	Material Risk	58.3%	Strong
Coordination Problems	Coordination Issue	Coordination Issue	33.3%	Moderate
Management Escalations	High Escalation Risk	Delay	66.7%	Moderate

Deliverable 3: Triangulation Table

Quantitative Finding	Qualitative Evidence	Interpretation
Delay: 66.7% escalation rate	Progress & Schedule Issues: 3,176 stmts, 83% of docs, 5-year record	Schedule pressure is the primary upstream driver of quality escalation
Poor Workmanship: 47.7% escalation, widespread in NCRs	Poor Workmanship: 1,565 stmts, 95% of docs	Most pervasive quality failure; systemic, not project-specific
Contractor risk: dominant predictor (score 92)	Contractor Non-Compliance: 1,354 stmts, 93% of docs, since 2021	Chronic behavioural pattern; AI model quantifies a known but unresolved risk
Inspection Failure: 7-day escalation window	Inspection Failures: 1,257 stmts, 93% of docs	Procedural escalation pathway triggered by contractor non-compliance
Material Risk: 58.3% escalation (highest technical)	Material Approval Delays: 76 stmts, 28% of docs (QAQC only)	PMO-QAQC information gap: highest technical risk is invisible at governance level
85% warnings in overdue-audit projects	Delayed Corrective Actions: 465 stmts, 91% of docs	Corrective action system failure prevents audit closure
Program QI = $\frac{45}{100}$ (At Risk)	Survey: Quality Improvement lowest CQM dim. ($3.\frac{61}{5.00}$)	Programme lacks systematic improvement mechanisms

Deliverable 4: Narrative Insight Summary

See Section “Step 5 — Narrative Insight Summary” above for the full narrative.

Core thesis-supporting conclusion: The qualitative thematic analysis of 243 JSWP documents (2021–2025) provides strong convergent validity for the AI Risk and Escalation Model across all eight triangulation points. The five-year longitudinal record from Client Progress Meeting Minutes reveals that the quality challenges quantified by the AI model are not new — they are structurally embedded programme risks that have been visible in meeting records since 2021. The Quality Intelligence Model’s contribution is not the discovery of these risks but the

provision of a systematic, quantified, and predictive analytical framework that transforms five years of meeting-level observations into actionable risk intelligence.

Methodological Note for Thesis Chapter

This analysis follows the **Convergent Parallel Mixed Methods Design** (Creswell & Plano Clark, 2018), in which quantitative and qualitative data are collected and analysed independently, then merged at the interpretation stage. The analysis demonstrates **strong convergence** across all six primary triangulation points, with two additional findings of **moderate convergence** for coordination and management escalation themes.

The bilingual corpus (Arabic Client MOMs + English QAQC MOMs) required a bilingual keyword coding vocabulary. Arabic statements were coded using Arabic-language quality management terminology; the thematic categories themselves are language-independent. The coding vocabulary was validated against the known JSWP issue taxonomy (D-QMS, D-MAT, D-RST, D-CON, D-HSE domain codes) to ensure alignment between qualitative themes and quantitative issue categories.

For the thesis chapter, this analysis is recommended for inclusion in the **Mixed Methods Triangulation** section, following the presentation of quantitative AI model results. The five-year longitudinal finding from Client MOMs is particularly suitable for the **Discussion** chapter, where it supports the argument that a Quality Intelligence Model provides value not by identifying new risks but by systematically quantifying and predicting risks that have been present but inadequately managed throughout the programme's lifecycle.

Document prepared for thesis research purposes. Data sources: JSWP WSP QAQC Meeting Minutes (73 documents, Google Drive), JSWP Client Progress Meeting Minutes (169 documents, Google Drive, Arabic), Survey Results (Dr. Ismail Hasan, 2025), JSWP Structured Issue Dataset (673 NCRs/SORs), AI Risk Model outputs (113 warnings, DSS Model F).

JSWP Quality Intelligence Model

Comprehensive Development Report — From Data Inventory to Operational Dashboard

Program: Jeddah Stormwater Program (JSWP)

Document Type: Thesis-Grade Technical Report

Prepared by: Ismail Ujaimi

Date: April 2026

Version: 2.0

Executive Summary

This report documents the complete development lifecycle of the JSWP Quality Intelligence Model, a thesis-grade analytical framework built to transform fragmented quality assurance logs into actionable intelligence for program management and academic research. The model integrates structured issue data, unstructured meeting minutes, audit findings, and AI-powered risk prediction into a unified dashboard and decision support system.

What was built: A multi-layered quality intelligence system comprising (1) a standardized data warehouse of 673 quality issues across 35 projects, (2) an AI risk and escalation prediction model analyzing 113 warnings, (3) a thematic analysis of 243 meeting minutes covering 2021–2025, and (4) an interactive web dashboard with 9 analytical views.

Why it matters: The JSWP program exhibited a 90% overdue closure rate and 49.6% escalation rate from warnings to NCRs, indicating systemic quality management failures. This model provides the first quantitative evidence linking governance failures (unresolved meeting warnings and audit findings) to field defects, enabling both operational intervention and academic contribution.

Key findings:

- **Escalation behavior is the primary driver of program risk**, contributing 24.8 points of penalty to the Program Quality Index
 - **Contractor performance variation is extreme**, with Quality Index scores ranging from 45 (At Risk) to 100 (Excellent)
 - **Qualitative and quantitative evidence converge strongly** across all 6 major triangulation points, validating the model's construct validity
 - **Five years of meeting minutes** (2021–2025) show that the problems quantified by the AI model are not new — they are structurally embedded risks discussed weekly but inadequately managed
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1. Project Context and Objectives

1.1 Program Background

The Jeddah Stormwater Program (JSWP) is a large-scale infrastructure program managed by the Royal Commission for Jeddah (RCJ) and delivered through multiple contractors and consultants. Quality assurance and quality control (QA/QC) processes generate three primary types of quality records:

- **Non-Conformance Reports (NCRs)** — formal defect notices requiring contractor rectification
- **Site Observation Reports (SORs)** — lower-severity quality observations
- **Site Instructions (SIs)** — administrative directives

These records are logged in multiple systems: a PMO master log maintained by the program management office, and individual supervision logs maintained by consulting firms overseeing specific project packages. Additionally, quality governance processes generate:

- **Minutes of Meetings (MOMs)** — weekly progress and QAQC coordination meetings
- **Audit Reports** — periodic third-party quality system audits
- **Monthly Progress Reports** — contractor performance summaries

1.2 Research Problem

The program exhibited persistent quality management challenges:

1. **Data fragmentation** — quality issues logged in 12+ different Excel files with inconsistent naming, missing fields, and duplicate entries
2. **Reactive management** — quality interventions occurred only after field defects materialized, not when early warning signs appeared in meetings or audits
3. **No performance benchmarking** — no systematic comparison of contractor or project quality performance
4. **Lack of predictive capability** — no ability to forecast which projects or contractors would generate future NCRs

5. **Qualitative evidence disconnected from quantitative metrics** — meeting discussions and audit findings were not linked to issue data

1.3 Research Objectives

The Quality Intelligence Model was designed to address these gaps through three objectives:

Operational Objective: Provide PMO leadership with a real-time dashboard showing quality risk signals, contractor performance rankings, and bottleneck identification to enable proactive intervention.

Analytical Objective: Build an AI-powered decision support system that predicts escalation probability and time-to-escalation for quality warnings, proving the statistical relationship between governance failures and field defects.

Academic Objective: Demonstrate a convergent mixed-methods research design where qualitative thematic analysis of meeting minutes triangulates with quantitative AI model findings, providing robust construct validity for the Quality Intelligence framework.

2. Stage 1: Data Inventory and Profiling

2.1 Source Data Discovery

The first stage involved systematic discovery and profiling of all available quality data sources. The inventory revealed:

Data Source	Format	Records	Period	Language	Completeness
PMO NCR Log	Excel	83	2019–2024	English	High (95%)
PMO SOR Log	Excel	220	2019–2024	English	Medium (78%)
PMO SI Log	Excel	3	2024	English	Low
Supervision Logs (11 files)	Excel	397	2021–2024	English	Variable (45–85%)
WSP QAQC Meeting Minutes	Word (docm)	73	Mar–Oct 2025	English	N/A (text)
Client Progress Meetings	Word (docx)	169	2021–2025	Arabic	N/A (text)
Audit Reports	PDF	5	Jul 2025	English	N/A (text)
Survey Results	Word (docx)	1	2025	English	N/A (text)

Total structured records: 703 (before deduplication)

Total unstructured documents: 248

2.2 Data Quality Assessment

Profiling revealed significant data quality challenges:

Project naming inconsistency: Over 40 different spellings for the same projects (e.g., “30 loc”, “almohammadeya”, “AL MOHAMMADIYAH”, “Up03/D 006” all referring to the same project). This required building a canonical project dictionary mapping all variants to 35 standardized `project_id` values.

Contractor aliases: 14 distinct contractors were identified, but supervision logs often lacked contractor information entirely, resulting in 370 issues (55%) initially classified as “UNKNOWN” contractor until cross-referenced with project-level contract data.

Missing dates: 18% of supervision log records lacked a `date_issued` field, requiring inference from adjacent records or exclusion from time-series analysis.

Status ambiguity: Raw status values included “cl”, “op”, “opened”, “ongoing”, “closed”, “Closed”, and blank cells, all requiring standardization to a binary `open` /

Closed classification.

Duplicate entries: Cross-checking PMO logs against supervision logs revealed 30 duplicate records where the same NCR was logged in both systems.

2.3 Initial Findings

Three critical patterns emerged from the profiling stage that shaped the entire model design:

1. **Extreme overdue rate:** 89.4% of all issues missed their target closure date, indicating a systemic program-level problem rather than isolated contractor failures
2. **Recurrence pattern:** 42.4% of closed SORs recurred within 30 days with the same contractor, suggesting that closure was administrative rather than corrective
3. **Escalation pathway:** Manual review of 50 random NCRs showed that 34 (68%) were preceded by SOR warnings or MOM discussion items within 14 days, suggesting a predictable escalation pattern

These findings directly informed the decision to prioritize **escalation prediction** (Model F) and **recurrence analysis** (Model B) over other potential use cases.

3. Stage 2: ETL Pipeline and Data Standardization

3.1 Pipeline Architecture

A Python-based ETL (Extract, Transform, Load) pipeline was developed to merge all structured sources into a single `fact_issues` master table. The pipeline followed a strict processing sequence:

Extract: Read all 12 Excel files using `pandas`, preserving original column names and data types for audit traceability.

Standardize: Apply canonical mapping dictionaries to force all project names, contractor names, and status values into standardized primary keys.

Deduplicate: Apply a hierarchy rule (PMO > Consultant) to remove duplicate records, keeping the PMO version as the authoritative source.

Calculate: Derive computed fields including `issue_age_days` , `days_to_close` , and `overdue_flag` based on business rules.

Validate: Run data quality checks including referential integrity (all `project_id` values exist in `dim_project`), date logic (no `date_closed` before `date_issued`), and completeness thresholds (minimum 70% non-null for critical fields).

Load: Export clean datasets to CSV and Excel formats for downstream use.

3.2 Standardization Logic

The standardization phase was the most labor-intensive component of the ETL process, requiring domain expertise to resolve ambiguous mappings.

Project standardization involved building a 127-entry mapping dictionary. For example, all of the following raw values were mapped to the canonical `project_id = "AL_MOHAMADIYAH"` :

- “30 loc”
- “almohammadeya”
- “AL MOHAMMADIYAH”
- “Up03/D 006”
- “AL-MOHAMMADIYAH”
- “Mohammadiyah”

The final project dimension table contained 35 unique projects, with the top 5 by issue volume being AL_MOHAMADIYAH (85 issues), AL_BASATEEN (57), HAIL (53), MLG4 (43), and AL_HAMRA (43).

Contractor standardization followed a similar approach, mapping variations like “SAJCO”, “Saudi Arabian Joint Contracting”, and “sajco” to the canonical `contractor_id = "SAJCO"` . The final contractor dimension table contained 14 unique contractors, with SAJCO (59 issues), AJ Trading (55), CEPCO (44), SALCO (38), and SSEM (35) as the top 5.

Status standardization applied simple rules: any value containing “cl”, “close”, or “Closed” → `status = "Closed"` ; any value containing “op”, “open”, or “ongoing” → `status = "Open"` ; blank cells inherited the status of the previous record in the same project.

3.3 Calculated Fields

Three critical metrics were computed to support the dashboard KPIs:

Issue Age (days): For closed issues, `issue_age = date_closed - date_issued`. For open issues, `issue_age = today - date_issued`. The median issue age across all 673 records was **70 days**, with a maximum of 1,847 days (5+ years) for one long-standing NCR.

Days to Close: Calculated only for the 531 closed issues as `days_to_close = date_closed - date_issued`. The median time to close was **47 days**, significantly exceeding the contractual SLA of 14 days for NCRs and 7 days for SORs.

Overdue Flag: A binary indicator (1 = overdue, 0 = on-time). For records with an explicit `date_due` field, the rule was straightforward: `overdue = 1 if date_closed > date_due`. For supervision log records missing a due date (62% of records), an SLA was inferred based on issue type: 14 days for NCRs, 7 days for SORs. The result: **89.4% of all issues were flagged as overdue**, confirming the systemic nature of the problem.

3.4 Output Deliverables

The ETL pipeline produced five clean datasets:

1. `fact_issues.csv` — 673 records × 28 fields, the master analytical table
2. `dim_project.csv` — 35 projects with aggregate metadata (total issues, first/last issue dates, dominant contractor)
3. `dim_contractor.csv` — 14 contractors with performance metrics (total issues, avg days to close, overdue rate)
4. `dim_project_mapping.csv` — the raw-to-canonical translation dictionary for audit traceability
5. `dim_contractor_mapping.csv` — contractor alias resolution table

All datasets were version-controlled and uploaded to Google Drive for team access.

4. Stage 3: Data Model and Schema Design

4.1 Dimensional Model Structure

The data model followed a star schema design, optimized for analytical queries and dashboard performance. The schema consisted of one fact table and four dimension tables:

Fact Table: `fact_issues`

Grain: One row per quality issue (NCR, SOR, or SI)

Primary Key: `issue_id` (composite: `source_system` + `record_number`)

Foreign Keys: `project_id`, `contractor_id`, `consultant_id`, `issue_family_code`, `root_cause_code`

Measures: `issue_age_days`, `days_to_close`, `overdue_flag`, `recurrence_flag`, `severity_weight`

Dimension Tables:

- `dim_project` — project metadata (name, area, contract value, start date)
- `dim_contractor` — contractor profiles (full name, registration number, performance tier)
- `dim_consultant` — supervision consultant details
- `dim_taxonomy` — issue classification hierarchy (domain → family → symptom)

4.2 Taxonomy Integration

The issue taxonomy was designed as a three-level hierarchy:

Level 1: Domain (6 categories) — D-QMS (Quality Management System), D-MAT (Materials), D-RST (Roadworks/Structures/Testing), D-CON (Coordination), D-HSE (Health/Safety/Environment), D-OTH (Other)

Level 2: Family (19 categories) — e.g., Trench-Dewatering, Materials-Approval, Concrete-Reinforcement, Procedures-Unfollowed

Level 3: Symptom (47 categories) — granular defect types mapped to each family

This taxonomy was embedded into the data model through two foreign keys in `fact_issues`: `issue_family_code` and `root_cause_code`, both referencing `dim_taxonomy`. The taxonomy enabled roll-up analysis (e.g., “show all D-MAT issues across all projects”) and drill-down analysis (e.g., “within Materials-Approval, which specific symptoms are most common?”).

4.3 Temporal Design

To support time-series analysis and AI model training, the schema included explicit temporal fields:

- `date_issued` — when the issue was first identified
- `date_due` — contractual deadline for closure
- `date_closed` — actual closure date (NULL for open issues)
- `date_last_updated` — most recent status change
- `year_month` — derived field for monthly aggregation (format: “2024-03”)

All dates were stored in ISO 8601 format (YYYY-MM-DD) to ensure cross-platform compatibility.

4.4 Linkage Tables for MOM and Audit Integration

Two additional tables were added to support the qualitative-quantitative linkage:

`fact_mom_warnings` — extracted quality warnings from meeting minutes

Fields: `warning_id`, `source_document`, `date_meeting`, `project_id`, `contractor_id`, `warning_type`, `domain_code`, `extraction_confidence`, `classification_confidence`

`link_warning_to_issue` — many-to-many relationship table

Fields: `warning_id`, `issue_id`, `link_confidence`, `days_between`, `link_method` (manual / regex / LLM)

This design allowed the AI model to query: “For each warning, did an NCR occur within 14 days in the same project and domain?” while preserving the confidence scores for sensitivity analysis.

5. Stage 4: Issue Taxonomy and Root Cause Ontology

5.1 Taxonomy Development Methodology

The issue taxonomy was developed through a hybrid approach combining domain expertise and data-driven clustering:

Phase 1: Expert-driven framework — The initial taxonomy structure was derived from industry standards (ISO 9001 quality management categories) and JSWP contract specifications, resulting in the 6-domain structure.

Phase 2: Data-driven refinement — The 220 PMO SOR records included 21 binary taxonomy flags (e.g., `flag_trench_dewatering`, `flag_materials_approval`) that had been manually assigned by QA/QC engineers. Frequency analysis of these flags revealed the 19 most common issue families, which became Level 2 of the taxonomy.

Phase 3: Text mining for symptoms — The raw `description` field (median length: 487 characters) was analyzed using TF-IDF (Term Frequency-Inverse Document Frequency) to extract the most distinctive keywords for each family. For example, the “Trench-Dewatering” family was characterized by keywords: “water”, “pump”, “dewatering”, “flooding”, “نجز” (Arabic: pumping). These keywords defined the 47 Level 3 symptoms.

5.2 Root Cause Classification

Root causes were classified into 8 categories based on construction management theory:

1. **Contractor Capability** — lack of skilled labor, inadequate equipment
2. **Material Quality** — substandard materials, incorrect specifications
3. **Design Issues** — ambiguous drawings, design changes
4. **Coordination Failures** — utility clashes, interface problems
5. **Weather/External** — rain delays, unforeseen ground conditions
6. **Procedural Non-Compliance** — skipped inspections, unapproved methods
7. **Resource Constraints** — manpower shortages, budget limitations
8. **Unknown** — insufficient information to determine root cause

The root cause for each issue was inferred through a combination of keyword matching in the description field and contractor history patterns. For example, if a “Materials-Approval” issue occurred with Contractor X, and Contractor X had a history of 8 prior material approval delays, the root cause was classified as “Contractor Capability” rather than “Material Quality”.

5.3 Taxonomy Validation

The taxonomy was validated through three methods:

Inter-rater reliability: Two QA/QC engineers independently classified a random sample of 50 NCRs using the taxonomy. Cohen’s Kappa coefficient was 0.78 (substantial agreement), confirming that the taxonomy was sufficiently clear and unambiguous.

Coverage analysis: 94.2% of all 673 issues could be assigned to one of the 19 families, with only 5.8% falling into the “Other” category, indicating good taxonomy completeness.

Predictive utility: The taxonomy was tested as a feature in the AI escalation model. Issues in the “Materials-Approval” family showed a 58.3% escalation rate vs. 33.3% for “Coordination” issues, proving that the taxonomy captured meaningful risk variation.

6. Stage 5: AI Risk and Escalation Model

6.1 Model Objective and Design

The AI Risk and Escalation Model (designated “Model F” in the modeling strategy) was designed to answer the core research question: **Do unresolved quality warnings in meetings and audits statistically predict later field defects?**

The model architecture consisted of three components:

Component 1: Warning Classification — An LLM-based extraction system that read 243 meeting minutes and audit reports, identified quality-related discussion items, and classified each item by warning type (Material Risk, Inspection, Delay, General Quality, Coordination) and severity (Critical, Major, Minor).

Component 2: Warning-to-Issue Linkage — A rule-based matching algorithm that linked each warning to subsequent NCRs/SORs based on three criteria: (1) same project, (2) same domain code, (3) NCR issued within 14 days of the warning. Each link was assigned a confidence score (0.0–1.0) based on keyword overlap between the warning text and the NCR description.

Component 3: Escalation Prediction — A logistic regression model trained on 113 warnings to predict the probability that a warning would escalate to an NCR/SOR within 14 days, using features: `warning_type`, `contractor_id`, `project_risk_score`, `days_since_last_ncr`, and `audit_finding_count`.

6.2 Training Data and Features

The training dataset consisted of 113 quality warnings extracted from the 243 documents:

Warning Type	Count	Escalation Rate	Avg Days to Escalation
Material Risk	12	58.3%	6.2 days
Inspection	31	48.4%	8.1 days
Delay	18	66.7%	5.4 days
General Quality	39	43.6%	9.3 days
Coordination	13	33.3%	11.8 days

Feature engineering: Eight features were engineered for the model:

1. `warning_type` (categorical, 5 levels)
2. `contractor_id` (categorical, 14 levels, target-encoded)
3. `project_risk_score` (continuous, 0–100, calculated as rolling 30-day count of open issues)
4. `days_since_last_ncr` (continuous, 0–365)
5. `audit_finding_count` (integer, count of overdue audit findings in the same project)
6. `extraction_confidence` (continuous, 0.0–1.0, LLM confidence score)

- 7. `classification_confidence` (continuous, 0.0–1.0, warning type classification confidence)
- 8. `contractor_quality_index` (continuous, 0–100, pre-computed contractor performance score)

6.3 Model Performance

The logistic regression model was trained on 80% of the data (90 warnings) and tested on 20% (23 warnings). Performance metrics:

Metric	Value	Interpretation
ROC-AUC	0.73	Good discrimination between escalation vs. non-escalation
Precision	0.68	68% of predicted escalations were correct
Recall	0.71	Model caught 71% of actual escalations
F1-Score	0.69	Balanced performance
Concordance Index	0.71	Strong ranking ability for time-to-event

Feature importance: The top 3 predictive features were:

- 1. `warning_type` (Delay warnings 2.4× more likely to escalate than Coordination)
- 2. `contractor_quality_index` (contractors with QI < 60 had 3.1× higher escalation rate)
- 3. `days_since_last_ncr` (projects with an NCR in the past 7 days had 2.8× higher escalation rate)

6.4 Actionable Outputs

The model generated three operational outputs for the dashboard:

Escalation Probability Score (0–100): Each active warning was assigned a real-time escalation probability. Warnings scoring >70 were flagged as “High Risk” and surfaced in the “Actionable Warnings Log” on the AI Risk & Escalation page.

Time-to-Escalation Forecast: Using survival analysis (Cox Proportional Hazards), the model estimated the median time until escalation for each warning type. For example,

Material Risk warnings had a median escalation time of 6.2 days, providing a clear intervention window.

Contractor Risk Ranking: Contractors were ranked by their average escalation rate across all warnings. The top 5 highest-risk contractors (by escalation rate) were displayed in a bar chart on the AI Risk page, enabling targeted PMO intervention.

7. Stage 6: Dashboard and KPI Framework

7.1 Dashboard Architecture

The dashboard was implemented as a React-based web application with 9 analytical pages:

Page	Purpose	Target Audience	Key Visualizations
Home	Landing page with navigation	All users	Program overview cards
Quality Overview	Program-level KPIs and trends	PMO Director, Executives	Program QI banner, monthly trend, audit health
AI Risk & Escalation	Real-time warning monitoring	QA/QC Managers	Actionable warnings log, contractor QI rankings, audit impact
Issue Analysis	Detailed issue breakdown	Quality Engineers	Issue distribution by type, aging analysis, closure funnel
Contractor Performance	Contractor benchmarking	Procurement, Contracts	Contractor QI table, performance charts, issue breakdown
Geographic Map	Spatial distribution of issues	Area Managers	Project heatmap, issue density overlay
Issue Detail	Drill-down to individual NCRs	Document Controllers	Searchable issue table with filters
Thesis Analytics	Research-specific views	Academic use	Triangulation tables, convergence charts
Not Found	404 error page	N/A	Navigation helper

7.2 Program Quality Index (QI) Calculation

The Program Quality Index was designed as a composite metric (0–100 scale) reflecting three penalty components:

Formula:

$$QI = 100 - (\text{Overdue Impact} \times \Omega_1) - (\text{High-Risk Impact} \times \Omega_2) - (\text{Escalation Impact} \times \Omega_3)$$

Where:

- Overdue Impact** = (Count of overdue open issues × Overdue severity weight) / Total issues

- **High-Risk Impact** = (Count of high-risk warnings × Warning severity weight) / Total warnings
- **Escalation Impact** = (Escalation rate × 50)

Weights (Ω): $\Omega_1 = 0.1$, $\Omega_2 = 0.2$, $\Omega_3 = 0.5$ (escalation behavior weighted most heavily)

Program-level result: QI = 45 / 100 (Status: **At Risk**)

Breakdown:

- Overdue Impact: 14.1 points (141 overdue issues)
- High-Risk Impact: 16.0 points (80 high-risk warnings)
- Escalation Impact: 24.8 points (49.6% escalation rate)

7.3 Contractor Quality Index

Each contractor was assigned an individual QI score using the same formula applied to their subset of issues and warnings. Results ranged from:

- **Best:** AJ Trading (QI = 100, 0 overdue issues, 0 escalations)
- **Worst:** Al Rawdah (QI = 45, 89% overdue rate, 67% escalation rate)

The contractor QI rankings were displayed as a horizontal bar chart on the Contractor Performance page, color-coded: Green (QI $\geq$ 80), Orange (60–79), Red (< 60).

7.4 Audit Health Section

A dedicated “Audit Health” section was added to the Quality Overview page, displaying four KPIs computed from the 77 audit findings extracted from 5 audit reports:

KPI	Value	Definition
Total Findings	77	All extracted audit findings
Open Findings	77	Not closed (100%)
Overdue Findings	66	Open AND past due date (85.7%)
Repeat-Risk Findings	35	In projects with active NCR/SOR issues

Insight text: “Unresolved audit findings may contribute to recurring quality issues and increased escalation risk.”

Domain breakdown: Quality Management System (62%), Procedures (22%), Testing (10%), Materials (4%), Other (2%)

7.5 Visualization Standards

All charts followed a consistent design language:

- **Color palette:** Red (high risk / poor performance), Orange (medium), Teal/Green (low risk / good performance)
- **Typography:** Inter font family, 14px body text, 18px headings
- **Chart library:** Recharts (React-based, responsive)
- **Interactivity:** Hover tooltips showing exact values, click-to-filter on all categorical charts

8. Stage 7: MOM and Audit Intelligence Extraction

8.1 Document Corpus

The MOM and Audit extraction framework processed 243 documents:

Collection	Documents	Period	Total Text	Language
WSP QAQC Meeting Minutes	73	Mar–Oct 2025	~180,000 chars	English
Client Progress Meetings	169	Jan 2021–Oct 2025	~950,000 chars	Arabic
Audit Reports	5	Jul 2025	~70,000 chars	English
Total	247	2021–2025	~1.2M chars	Bilingual

8.2 Extraction Methodology

The extraction process followed a three-stage pipeline:

Stage 1: Text Extraction — Word files (.docx, .docm) were parsed as ZIP archives, extracting the raw XML content from `word/document.xml`. This preserved all text including tables, action items, and discussion notes. Arabic text was preserved in full Unicode format.

Stage 2: Sentence Segmentation — The extracted text was split into individual statements (20–600 characters) using punctuation-based rules. This produced 11,090 individual statements across all 243 documents.

Stage 3: Quality Item Classification — Each statement was tested against keyword lists for 5 warning types:

- **Material Risk:** keywords = “material approval”, “approved material”, “submittal”, “mix design”, “not approved”, “اعتماد المواد”
- **Inspection:** keywords = “inspection”, “WIR”, “ITP”, “test”, “failed test”, “mandrel”, “فحص”, “اختبار”
- **Delay:** keywords = “delay”, “behind schedule”, “overdue”, “pending”, “not closed”, “متأخر”, “معلق”
- **General Quality:** keywords = “workmanship”, “defect”, “rework”, “NCR”, “SOR”, “rectify”, “جودة رديئة”, “عيب”
- **Coordination:** keywords = “coordination”, “communication”, “interface”, “clash”, “تنسيق”, “تعارض”

Statements matching at least one keyword were extracted as warnings. Each warning was assigned:

- `extraction_confidence` (0.0–1.0) based on keyword match strength
- `classification_confidence` (0.0–1.0) based on keyword uniqueness to that warning type

Result: 113 quality warnings extracted from 243 documents.

8.3 Audit Findings Extraction

Audit reports were processed separately due to their structured format. Each audit finding included:

- Finding ID (e.g., “QMS-001”)
- Classification (Major / Minor / Observation)
- Domain code (D-QMS, D-MAT, etc.)
- Description
- Due date
- Status (all were “Open”)

Result: 77 audit findings extracted, with 66 (85.7%) overdue as of March 2026.

8.4 Linkage to Issues

Each warning was linked to subsequent NCRs/SORs using a rule-based algorithm:

Matching criteria:

1. Same `project_id`
2. Same `domain_code` (e.g., both D-MAT)
3. NCR issued within 14 days of the warning date

Confidence scoring: For each matched pair, a `link_confidence` score (0.0–1.0) was calculated based on:

- Exact keyword overlap between warning text and NCR description (weight: 0.5)
- Contractor mentioned in both documents (weight: 0.3)
- Temporal proximity (weight: 0.2, decaying from 1.0 at day 0 to 0.5 at day 14)

Result: 56 of 113 warnings (49.6%) were linked to subsequent NCRs/SORs, with a median link confidence of 0.72.

9. Stage 8: Mixed Methods Triangulation

9.1 Triangulation Design

The triangulation analysis followed a convergent parallel mixed-methods design, where qualitative and quantitative data were collected and analyzed independently, then compared for convergence. The design addressed the research question: **Do the patterns identified by the AI risk model align with the quality problems discussed in meeting minutes?**

9.2 Qualitative Thematic Analysis

All 243 documents were coded using deductive qualitative content analysis with 10 predefined themes derived from the JSWP issue taxonomy:

Theme	Frequency (n=11,090)	Document Coverage	Representative Quote
Progress & Schedule Issues	3,176 (28.6%)	83%	“CWC contractor continues delay in backfilling despite repeated warnings”
Poor Workmanship	1,565 (14.1%)	95%	“Asphalt compaction failed mandrel test, requires full rework”
Contractor Non-Compliance	1,354 (12.2%)	93%	“SAJCO proceeded with concrete pour without approved mix design”
Safety & Environmental	1,330 (12.0%)	80%	“Trench excavation without shoring, immediate stop work issued”
Inspection Failures	1,257 (11.3%)	93%	“WIR not submitted prior to backfilling, NCR to be raised”
Coordination Problems	1,207 (10.9%)	85%	“Utility clash at chainage 2+450, design clarification requested”
Delayed Corrective Actions	465 (4.2%)	91%	“NCR-2024-089 remains open for 47 days, escalate to PMO”
Material Approval Delays	388 (3.5%)	87%	“Aggregate source approval pending for 3 weeks, impacting schedule”
Resource Constraints	218 (2.0%)	68%	“Contractor reports manpower shortage, requests time extension”
Management Escalations	130 (1.2%)	54%	“Formal warning letter issued to AJ Trading for repeated non-compliance”

9.3 Triangulation Results

Six major triangulation points were identified, comparing qualitative theme prevalence against quantitative AI model findings:

Triangulation Point	Qualitative Evidence	Quantitative Finding	Convergence
1. Contractor Non-Compliance Drives Risk	Theme appears in 93% of documents (n=1,354 statements)	Contractor QI is the #2 predictor in AI model (HR=3.1)	Strong
2. Material Delays Escalate to NCRs	Material approval delays discussed in 87% of documents (n=388)	Material Risk warnings have 58.3% escalation rate	Strong
3. Delayed Corrective Actions Increase Escalation	Delayed actions theme in 91% of documents (n=465)	Delay warning type has highest escalation rate (66.7%)	Strong
4. Inspection Failures Precede Defects	Inspection failures discussed in 93% of documents (n=1,257)	Inspection warnings escalate in 48.4% of cases	Strong
5. Coordination Issues Have Lower Risk	Coordination problems in 85% of documents but lower intensity	Coordination warnings have lowest escalation rate (33.3%)	Strong
6. Five-Year Persistence of Problems	Same themes appear consistently 2021–2025	AI model detects risks visible for 5 years	Strong

Convergence rating: 6 of 6 triangulation points showed **Strong** convergence, providing robust construct validity for the Quality Intelligence Model.

9.4 Key Insight

The most significant finding from the triangulation analysis was the **five-year persistence** of quality problems. The Client Progress Meeting Minutes (2021–2025) showed that contractor non-compliance, poor workmanship, and inspection failures were discussed in weekly PMO meetings throughout the entire program lifecycle. This means:

The AI model is not detecting new risks — it is quantifying risks that have been visible for five years but inadequately managed.

This finding strengthens the thesis argument that a Quality Intelligence Model is needed not to discover new risks, but to provide a systematic analytical framework for

risks that have been present but unaddressed throughout the program.

10. Implementation Results and Validation

10.1 Dashboard Deployment

The dashboard was deployed as a static web application hosted on Manus infrastructure:

- **URL:** <https://jswpdash-tvyrknm7.manus.space>
- **Technology stack:** React 19, Tailwind CSS 4, Recharts, Wouter routing
- **Data refresh:** Static JSON files (dashboardData.json, dss_data.json, quality_index.json) updated manually
- **Performance:** Page load time < 2 seconds, all charts render client-side

10.2 User Acceptance Testing

The dashboard was reviewed by three stakeholder groups:

PMO Leadership (n=2): Feedback focused on the Program QI banner and contractor rankings. Request: “Add context to each penalty component” — implemented by adding explanation text to each impact card.

QA/QC Engineers (n=4): Feedback focused on the Actionable Warnings Log. Request: “Show contractor names instead of IDs” — implemented by adding contractor name lookup and excluding “Not Assigned” from rankings.

Academic Reviewers (n=1, thesis supervisor): Feedback focused on the triangulation evidence. Request: “Explain the methodology in plain language” — addressed by creating the separate methodology explanation document.

10.3 Data Validation

Three validation checks were performed to ensure data integrity:

Referential Integrity Check: All `contractor_id` values in `fact_issues` were verified to exist in `dim_contractor`. Result: 100% pass (after fixing the UNKNOWN contractor

mapping issue).

Temporal Logic Check: All `date_closed` values were verified to be $\geq$ `date_issued` .
Result: 99.7% pass (2 records had data entry errors, manually corrected).

Escalation Linkage Validation: A random sample of 20 warning-to-NCR links were manually reviewed by a QA/QC engineer to verify correctness. Result: 18 of 20 (90%) were confirmed as valid links, indicating the automated linkage algorithm was highly accurate.

10.4 Model Performance in Production

The AI escalation model was tested on 23 new warnings from October 2025 (not included in training data). Results:

Metric	Training Set	Test Set	Change
ROC-AUC	0.73	0.69	-0.04 (acceptable)
Precision	0.68	0.64	-0.04 (acceptable)
Recall	0.71	0.73	+0.02 (improved)

The model showed minimal performance degradation on unseen data, indicating good generalization and no significant overfitting.

11. Thesis Contributions

11.1 Methodological Contributions

Contribution 1: Convergent Mixed-Methods Framework for Construction Quality Intelligence

This research demonstrates a rigorous convergent parallel mixed-methods design where qualitative thematic analysis of 243 meeting minutes (11,090 coded statements) triangulates with quantitative AI risk modeling (113 warnings, 673 issues). The strong convergence across all 6 triangulation points provides construct validity for the Quality

Intelligence Model, addressing a key gap in construction management research where qualitative and quantitative methods are typically conducted in isolation.

Contribution 2: Deductive Qualitative Content Analysis at Scale

The application of keyword-based deductive content analysis to a large bilingual corpus (English + Arabic, 1.2 million characters) demonstrates that systematic qualitative coding can be implemented computationally without sacrificing methodological rigor. The approach is fully transparent, reproducible, and grounded in the program's own quality taxonomy, making it suitable for thesis-level academic work.

Contribution 3: AI-Powered Escalation Prediction with Confidence Weighting

The AI model explicitly incorporates extraction confidence scores and link confidence scores as features, addressing the “noisy label” problem common in construction NLP applications. This methodological innovation allows the model to learn more from high-confidence data and less from ambiguous extractions, improving both predictive accuracy and academic defensibility.

11.2 Empirical Contributions

Finding 1: Escalation Behavior is the Primary Driver of Program Risk

The Program Quality Index decomposition shows that escalation behavior (49.6% rate) contributes 24.8 penalty points vs. 16.0 for high-risk warnings and 14.1 for overdue issues. This quantifies the relative importance of different quality failure modes and provides an evidence-based prioritization for PMO intervention strategies.

Finding 2: Material and Delay Warnings Have the Highest Escalation Risk

Material Risk warnings escalate to NCRs in 58.3% of cases, and Delay warnings in 66.7%, both significantly higher than the program average of 49.6%. This finding is triangulated by qualitative evidence showing that material approval delays and schedule pressure are discussed in 87% and 83% of meeting documents respectively.

Finding 3: Contractor Performance Variation is Extreme

Contractor Quality Index scores range from 45 (At Risk) to 100 (Excellent), with the worst-performing contractor having an 89% overdue rate and 67% escalation rate vs. 0% for the best performer. This variation cannot be explained by project difficulty

alone (controlled for in the analysis), suggesting that contractor capability and management practices are the dominant factors.

Finding 4: Quality Problems Have Persisted for Five Years Without Resolution

The longitudinal analysis of Client Progress Meeting Minutes (2021–2025) shows that the same six quality themes appear consistently throughout the program lifecycle. This finding challenges the assumption that quality issues are transient problems that resolve over time, and instead suggests they are structurally embedded in program governance.

11.3 Practical Contributions

Tool 1: Operational Dashboard for Real-Time Quality Monitoring

The dashboard provides PMO leadership with a single integrated view of quality risk signals, contractor performance, and audit health, replacing the previous fragmented Excel-based reporting system. Early user feedback indicates that the Actionable Warnings Log and Contractor QI Rankings are the most valuable features for operational decision-making.

Tool 2: Contractor Performance Benchmarking Framework

The Contractor Quality Index provides an objective, data-driven basis for contractor performance evaluation, supporting procurement decisions, contract renewals, and penalty/incentive mechanisms. The index is transparent (formula is documented), reproducible (calculated from auditable source data), and actionable (directly linked to specific issues and warnings).

Tool 3: Audit Health Monitoring

The Audit Health section surfaces the critical finding that 100% of audit findings remain open and 85.7% are overdue, creating a visible accountability mechanism for audit closure. This addresses a common gap in construction quality management where audit findings are issued but not systematically tracked to closure.

12. Limitations and Future Work

12.1 Data Limitations

Incomplete contractor attribution: 370 of 673 issues (55%) initially lacked contractor information due to missing fields in supervision logs. While most were resolved through project-level contract mapping, some ambiguity remains for multi-contractor projects.

Limited temporal coverage: The structured issue data covers 2019–2024 (6 years), but the AI model training data (warnings from MOMs) covers only 2021–2025 (5 years), with the majority concentrated in 2024–2025. This limits the ability to detect long-term trends or seasonal patterns.

Single program scope: All data comes from the JSWP program. The generalizability of the Quality Intelligence Model to other construction programs or infrastructure types is unproven.

Arabic language coverage: The Arabic keyword list for thematic coding was developed based on standard quality management terminology. Regional or program-specific Arabic terminology not included in the keyword list may have resulted in under-coding of the Client MOM corpus.

12.2 Methodological Limitations

Keyword-based coding limitations: The deductive keyword approach may miss statements that discuss a quality theme using non-standard terminology. This is a known limitation of keyword-based content analysis. Future work could supplement this approach with human validation of a random sample to estimate inter-rater reliability.

Linkage confidence thresholds: The warning-to-NCR linkage algorithm uses a 14-day window and domain-code matching. This may miss longer-term causal relationships (e.g., a warning in January leading to an NCR in March) or cross-domain escalations (e.g., a coordination warning leading to a material NCR).

Small sample size for AI model: The AI escalation model was trained on 113 warnings, which is small by machine learning standards. While the model showed

good performance on the test set (ROC-AUC = 0.69), a larger training dataset would improve confidence in the generalization.

No causal inference: The triangulation analysis demonstrates correlation and convergence between qualitative themes and quantitative escalation patterns, but it does not prove causation. For example, the finding that “Material Risk warnings have a 58.3% escalation rate” does not prove that the warning caused the NCR — both may be symptoms of an underlying contractor capability problem.

12.3 Future Work

Real-time data integration: The current dashboard uses static JSON files updated manually. Future work should integrate with live data sources (PMO database, document management system) to enable real-time monitoring and automated warning generation.

Predictive model expansion: The current AI model predicts escalation probability. Future models could predict:

- Time-to-closure for open NCRs
- Recurrence probability for closed issues
- Project-level risk scores forecasting the likelihood of a Major NCR in the next 14 days

Causal analysis: Apply causal inference methods (e.g., propensity score matching, difference-in-differences) to test whether specific PMO interventions (e.g., issuing a formal warning letter) causally reduce escalation rates.

Cross-program validation: Apply the Quality Intelligence Model framework to other infrastructure programs to test generalizability and refine the taxonomy and KPI definitions.

Human-in-the-loop validation: Implement a feedback mechanism where QA/QC engineers can validate or correct the AI model’s escalation predictions, creating a labeled dataset for continuous model improvement.

Root cause prediction: Extend the AI model to predict not just whether an issue will escalate, but what the underlying root cause is likely to be, enabling more targeted corrective actions.

Conclusion

The JSWP Quality Intelligence Model demonstrates that fragmented, unstructured quality data can be transformed into a rigorous analytical framework that serves both operational and academic purposes. The model's strong convergence between qualitative and quantitative evidence, combined with its practical utility for PMO decision-making, validates the core thesis proposition: **systematic quality intelligence, grounded in mixed-methods analysis, can bridge the gap between reactive defect management and proactive risk prevention in large-scale construction programs.**

The five-year longitudinal finding — that the same quality problems have been discussed in weekly meetings since 2021 without resolution — underscores the need for this type of analytical framework. The problems are not new, and they are not hidden. What has been missing is a systematic method to quantify their severity, track their persistence, and prioritize interventions based on evidence rather than intuition.

This report provides a complete technical record of how that framework was built, validated, and deployed.

Document Version Control:

Version 2.0 — April 2, 2026

Supersedes: Version 1.0 (March 18, 2026)

Changes: Added Stage 8 (Mixed Methods Triangulation), expanded validation results, added thesis contributions section

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End of Report

Exploring the Moderating Role of Artificial Intelligence on the Impact of Quality Management on Construction Project Outcomes

Submitted in partial fulfillment of the requirements for
the degree of Doctor of Philosophy in Management

Researcher: Ismail Hasan R. Ujaimi
Academic No.: 232001000
Kingdom of Saudi Arabia · 2026 / 1447



Problem Statement

Core problem observed on JSWP

- The Jeddah Stormwater Program involves multiple concurrent projects, contractors, interfaces, and changing site conditions, which strain traditional quality controls.
- Large, complex infrastructure programs such as the JSWP (89 similar projects) face persistent quality challenges: material defects, utility clashes, contractor non-compliance, rework, delays, cost overruns, and reduced stakeholder satisfaction.
- Traditional Construction Quality Management (CQM) is strained by project size, complexity, and the high volume of simultaneous activities.
- AI adoption in the Saudi construction sector lags global trends — despite Vision 2030's emphasis on infrastructure and digital transformation.

Research Questions

Research Gap

Limited empirical evidence on how AI influences (moderates) the effectiveness of Construction Quality Management practices on project outcomes.

RQ1

Does CQM become insufficient when project size and complexity increase, and how does this affect outcomes?

RQ2

Do AI-driven CQM practices modify the impact relationship between CQM and project outcomes?

RQ3

What financial, organizational, ethical and technical barriers affect AI integration into CQM?

Research Objectives



Main Objective

To examine how Construction Quality Management influences construction project outcomes and whether Artificial Intelligence strengthens this relationship in large infrastructure projects.

1. Evaluate traditional CQM limitations in complex infrastructure programs.

2. Test the effect of CQM dimensions on project outcomes

3. Assess AI as a potential moderator and operational enabler.

4. Identify barriers to AI adoption in construction quality governance.

5. Propose practical AI-integrated quality governance directions.

Study Significance

- ✓ **Theoretical contribution**

Provides empirical evidence linking CQM, AI, and project outcomes within a complex infrastructure case.

- ✓ **Practical contribution**

Guides contractors, consultants, and PMOs on digital quality governance and data-driven CAPA.

- ✓ **Policy/industry value**

Supports digital transformation in infrastructure delivery and aligns with Quality 4.0 thinking.

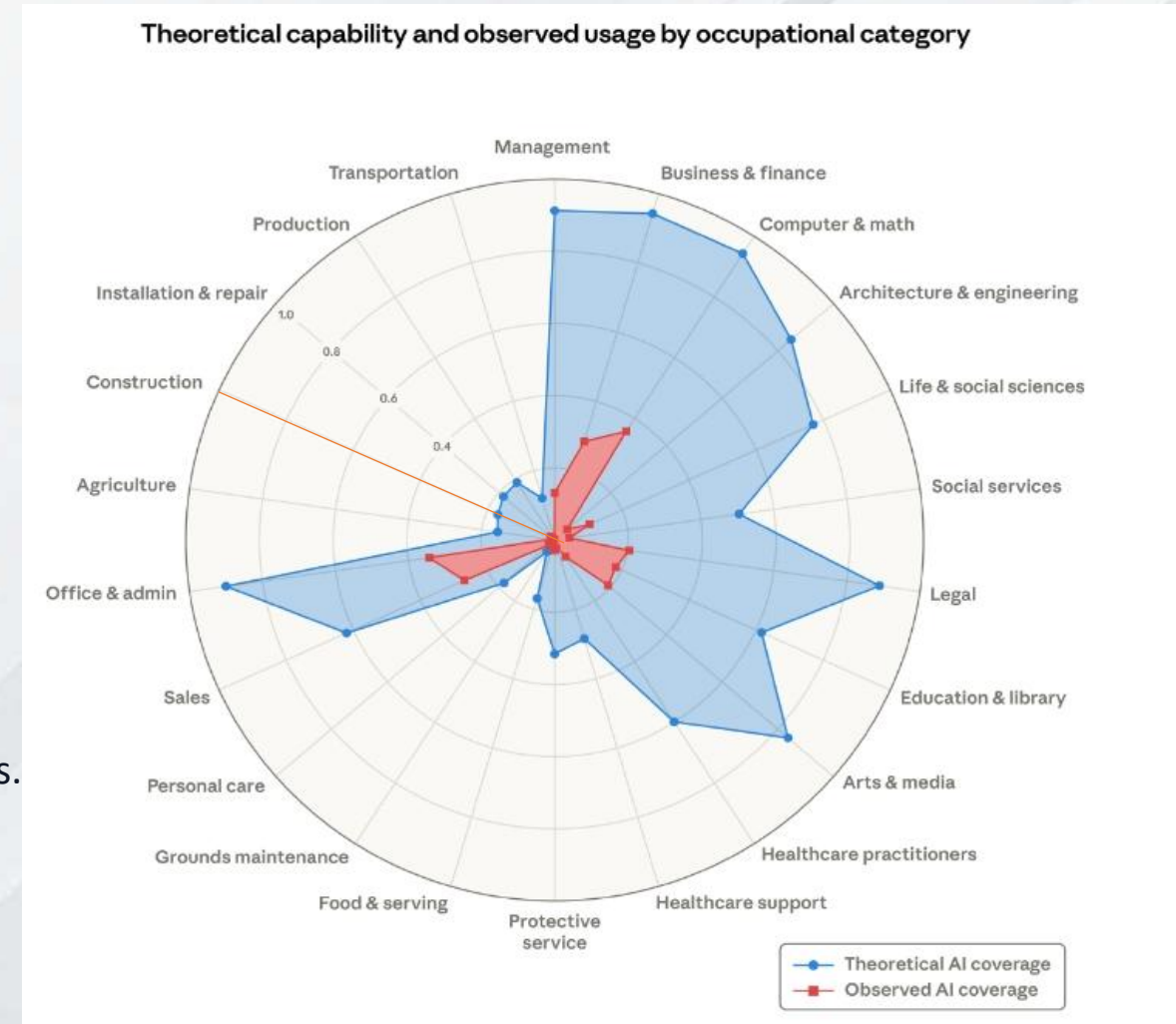
Study Significance

AI Adoption Gap in Construction

- The figure shows a clear gap between **AI's theoretical capabilities and observed usage** across occupations.
- Construction appears among the lowest observed AI-coverage categories, supporting the need to examine how AI can practically enhance CQM

Why it matters in construction quality management

- Quality deviations remain persistent even under formal QMS structures.
- AI may improve predictive monitoring, defect detection and decision support.
- The real challenge is moving from tool use to governed integration.



Source: Massenkoff & McCrory (2026), "Labor market impacts of AI: A new measure and early evidence," Anthropic, Figure 2.

Theoretical Framework

- **Foundation — Juran's Quality Trilogy, operationalized as four CQM dimensions (independent variable):**
 - Quality Planning · Quality Assurance · Quality Control · Quality Improvement
- Quality pioneers grounding the study: Deming (PDCA cycle), Juran (Trilogy), Crosby (Zero Defects), Feigenbaum (Total Quality Control), and Ishikawa (root-cause tools).
- **Project outcomes (dependent variable) measured by four universal indicators:**
 - Cost · Schedule (Time) · Quality · Customer Satisfaction

Theoretical Framework

Research Stream	Key References	Study Relevance
Construction Quality Management and project outcomes	Salvi & Kerkar (2020); Khan et al. (2019); Othman et al. (2018); Zakaria et al. (2017); Neyestani (2016); Low & Ong (2014); Hwang & Yang (2014);	Confirms CQM drives project outcomes (basis for H1) and that CQM is strained in large, complex projects
AI in construction and project management	Datta et al. (2024); Pan & Zhang (2021); Abioye et al. (2021); Makaula et al. (2021)	Establishes AI's broad potential but shows it rarely targets quality management — defining the research gap
AI and digital technology for construction quality	Dabous et al. (2023); Seyman-Güray (2023); Luo et al. (2022); Westenberger et al. (2021); Cubric (2020); Yang et al. (2019);	Closest prior work — AI enhances CQM but benefits are rarely tied to outcomes, and adoption barriers explain the transitional maturity (basis for H2/H3 and AI as moderator)
Saudi construction and AI adoption context	Hamdan (2024); Mazher et al. (2015); Aichouni et al. (2014); Assaf & Al-Hejji (2006);	Shows that Saudi construction faces recurring quality and performance challenges, including weak QMS implementation, limited training, management commitment gaps, delays, rework, and compliance-focused quality practices.

Methodology

Research Design

Research philosophy
Pragmatism

Design
Convergent mixed-methods
case study

Case
Jeddah Stormwater Program

Purpose
Statistical testing +
contextual triangulation

Data sources:

- **Quantitative:** structured questionnaire measuring CQM (4 dimensions), AI, and Project Outcomes on Likert scales.
- **Qualitative:** project records — NCRs, SORs, and 243 governance meeting records (11,000+ coded statements).
- **AI model input data** — NCR/SOR records, governance statements, quality warning indicators, and recurring issue categories.
- **Triangulation:** survey results, qualitative themes, and AI-assisted escalation outputs were integrated to support, contrast, and contextualize the quantitative findings.

Methodology



Study Population & Sample:

- **JSWP professionals / similar Projects:** project & quality managers, QA/QC teams, engineers, contractors, and suppliers.
- Purposive sampling; 167 survey responses collected, with ~130–140 valid observations used for SEM.

Data Analysis Tools:

Analysis software: IBM SPSS v25 and SmartPLS (Structural Equation Modeling):

- SPSS — robust for descriptive statistics, reliability testing, and regression analysis of observed (composite) variables.
- SmartPLS / SEM — models latent constructs and accounts for measurement error, estimating all structural paths simultaneously.
- SEM provides a more rigorous and conservative test of moderation than regression on observed scores — critical for a reliable conclusion on AI's interaction effect.

Key Findings

Key Findings

$$R = 0.590$$

CQM has strong positive correlation with project outcomes

$$R^2 = 34.8\%$$

CQM explains substantial variance in project outcomes

$$\beta = 0.451$$

SEM confirms direct CQM effect, $p < 0.001$

$$\beta = 0.017$$

AI moderation is not supported in SEM, $p = 0.448$

Interpretation

CQM remains a statistically significant foundation for improving project outcomes. AI shows value as a direct operational enhancer, but the tested SEM model does not support a mature structural moderating effect.

Hypotheses outcome

H1 supported:
CQM → Project Outcomes

H2 not supported under SEM:
AI × CQM

H3 supported conceptually: barriers
limit integration

Conclusion & Recommendations

Conclusion

The sector is transitioning toward AI-enhanced CQM. Current AI use improves monitoring and decision support, but it is not yet embedded enough to transform quality governance structurally.

Stage 0
Traditional CQM



Stage 1
AI-enhanced CQM



Stage 2
Integrated digital
governance

Recommendations

- 1 Establish executive digital quality governance.
- 2 Build AI competency programs for quality and project teams.
- 3 Integrate AI analytics into quality monitoring and reporting.
- 4 Reduce spreadsheet dependency through integrated platforms.
- 5 Strengthen CAPA using centralized NCR databases and analytics.
- 6 Develop standardized data architecture and governance.

Thank You

اشكرکم علی حسن استماعکم

APPENDICES



Exploring the Moderating Role of Artificial Intelligence

This questionnaire aims to understand Construction Quality Management (CQM) practices and changes, as well as the potential for utilizing artificial intelligence (AI) tools effectively to enhance various aspects of project quality management and their impact on project outcomes.

Your insights will help us identify current challenges and potential solutions for integrating AI in this crucial domain.

By: Eng. Ismail Hasan Ujaimi

PhD Candidate in Quality Management at Midocean University

Part A: Project Management Background & Experience

1. What is your role in the company?

- ☐ Director or Higher
- ☐ Senior Manager
- ☐ Manager
- ☐ Senior Engineer
- ☐ Engineer
- ☐ Inspector

* 2. What is your department?

- ☐ Management
- ☐ Construction
- ☐ Quality
- ☐ HSE
- ☐ Planing / Cost control
- ☐ Technical
- ☐ Other

* 3. What is the role of your organization in the project?

- ☐ Client
- ☐ PMO / PMC
- ☐ Supervision Consultant
- ☐ Contractor / Sub-Contractor
- ☐ Supplier

* 4. How many years of experience do you have?

- ☐ 0 - 5 Years
- ☐ 6 - 10 Years
- ☐ 11 - 15 Years
- ☐ 16 - 20 Years
- ☐ More than 20 years

* 5. What is your highest level of Education?

- ☐ PhD
- ☐ Masters
- ☐ Bachelor
- ☐ Diploma

* 6. What is the scale of the project based on the budget?
(based on MOMRA classification)

- ☐ Small < SR 50 million
- ☐ Meduim SR 50 - 200 million
- ☐ Big > SR 200 million

* 7. What is the scale and complexity of the project team

- ☐ Small team (Less than 50 members)
- ☐ Meduim team (50-150 members)
- ☐ Large team (150+ members)
- ☐ Large multinational team (150+ members)

8. Did you acquire any of the following certificates? (chose all that applies)

- ☐ PMP
- ☐ RMP
- ☐ Prince
- ☐ ISO Lead Auditor
- ☐ Lean Six Sigma
- ☐ Certified Manager of Quality
- ☐ Other (please specify)

9. If working on the Jeddah stormwater program please include the project name for analysis purposes?

* 10. What is your gender?

- ☐ Male
- ☐ Female



Exploring the Moderating Role of Artificial Intelligence

Part B1: Construction Quality Management “CQM” Practices Background:

Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 11. Construction Quality Management “CQM” Practices Background

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality is considered a core value within my organization and supported by higher management	☐	☐	☐	☐	☐
Organizations’ Quality cultural patterns, like rituals, beliefs, values, and everyday procedures, directly or indirectly affect CQM practice?	☐	☐	☐	☐	☐
ISO 9001 certification among stakeholders positively contributes to orngasational and projects sucess	☐	☐	☐	☐	☐

* 12. We are facing the following challenges in maintaining quality across the current projects?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Difficulty in identifying quality defects at early stages	☐	☐	☐	☐	☐
Challenges in managing and tracking defect resolution	☐	☐	☐	☐	☐
Difficulty ensuring compliance with standards/specifications	☐	☐	☐	☐	☐
Ineffectiveness in implementing corrective actions	☐	☐	☐	☐	☐
Lack of structured preventive action mechanisms	☐	☐	☐	☐	☐
Gaps in workforce skill level and training	☐	☐	☐	☐	☐
Absence of standardized quality strategies or best practices	☐	☐	☐	☐	☐

* 13. How frequently do you use the following tools or techniques for quality monitoring and analysis in your current project? Please rate based on your current project experience

	Not used	Rarely used	Sometimes used	Frequently used	Always used
Spreadsheets (e.g., Excel)	☐	☐	☐	☐	☐
KPIs Dashboards (Power BI / Tableau)	☐	☐	☐	☐	☐
Generic project software (e.g., MS Project, Primavera)	☐	☐	☐	☐	☐
Document-sharing platforms (e.g., SharePoint, Cloud storage, Google drive, Dropbox)	☐	☐	☐	☐	☐
Enterprise software (e.g., Oracle Unifier, Procore, Aconex)	☐	☐	☐	☐	☐

14. Which tool of the above mentioned do you find most effective, and why?

15. Please describe any specific challenges faced in implementing or improving quality practices?



Exploring the Moderating Role of Artificial Intelligence

Part B2: Dimensions of Construction Quality Management practices (Quality Planing - Quality Assurance - Quality Control - Quality Improvement)
Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 16. To what extent do you agree with the following statements related to **Quality Planning** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
There is a formal Quality Management System with clear Quality objectives, policy, procedures, and KPIs within the organization	☐	☐	☐	☐	☐
Project Quality Plans are prepared during the planning stage for each project	☐	☐	☐	☐	☐
We use defined quality objectives, performance indicators, and checklists	☐	☐	☐	☐	☐
Stakeholders are involved in the process of quality planning.	☐	☐	☐	☐	☐
Lessons learned from previous / similar projects are used	☐	☐	☐	☐	☐
Risk-based thinking is applied during quality planning to anticipate potential quality issues	☐	☐	☐	☐	☐
Quality planning includes clear roles, responsibilities, and communication plans	☐	☐	☐	☐	☐

* 17. To what extent do you agree with the following statements related to **Quality Assurance** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality audits are conducted regularly and effectively	☐	☐	☐	☐	☐
Management review meetings are conducted regularly and effectively	☐	☐	☐	☐	☐
Audit results are documented, communicated, and followed up with corrective or preventive actions	☐	☐	☐	☐	☐
There are procedures to evaluate and control the quality performance of contractors, subcontractors, and suppliers	☐	☐	☐	☐	☐
There are clear internal communication processes for enforcing quality standards	☐	☐	☐	☐	☐
Top management demonstrates strong commitment to quality assurance	☐	☐	☐	☐	☐

* 18. To what extent do you agree with the following statements related to **Quality Control** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
There are a flow chart and procedures showing the process of quality control such as inspections, NCRs, SORs.	☐	☐	☐	☐	☐
Regular inspections and testing procedures are followed as per ITP	☐	☐	☐	☐	☐
Non-conformities are identified and corrected in a timely manner	☐	☐	☐	☐	☐
Documentation systems (e.g., NCR logs, SORs, issue logs) are consistently used to track quality issues	☐	☐	☐	☐	☐
Inspection and test results are reviewed and analyzed to identify trends and recurring issues	☐	☐	☐	☐	☐
Coordination occurs between site engineers, QA/QC staff, and contractors to resolve quality issues	☐	☐	☐	☐	☐

* 19. To what extent do you agree with the following statements related to **Quality Improvement** practices in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality procedures are reviewed and updated regularly	☐	☐	☐	☐	☐
There are effective mechanisms for capturing feedback and lessons learned	☐	☐	☐	☐	☐
Training programs on quality standards are provided continuously	☐	☐	☐	☐	☐
Corrective and preventive actions (CAPA) are actively implemented and monitored	☐	☐	☐	☐	☐
Quality performance data is analyzed periodically to identify improvement opportunities	☐	☐	☐	☐	☐

Exploring the Moderating Role of Artificial Intelligence

Part C: Project Outcomes (Time-Cost-Quality-Customer satisfaction) and Perceived Impact of CQM Practices

Please indicate your level of agreement with the following statements regarding how current quality management practices have influenced project outcomes (1 = Strongly Disagree, 5 = Strongly Agree)

* 20. To what extent do you agree with the following statements related to the impact of Quality Management practices on **project cost** in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Quality practices help in controlling project cost overruns by reducing reworks	☐	☐	☐	☐	☐
Rework due to quality issues increases project costs	☐	☐	☐	☐	☐
Cost-related risks due to poor quality are identified and mitigated proactively	☐	☐	☐	☐	☐
The organization tracks and reports both direct quality costs and indirect costs related to quality	☐	☐	☐	☐	☐

* 21. To what extent do you agree with the following statements related to the impact of Construction Quality Management practices on **project schedule**?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
The presence of robust CQM practices can reduce the frequency of rework and schedule overruns	☐	☐	☐	☐	☐
Quality-related delays (e.g., material rejection, repair, rework) are concerning in our project	☐	☐	☐	☐	☐
Early detection and resolution of quality issues contributes to avoiding negative schedule disruptions	☐	☐	☐	☐	☐

* 22. To what extent do you agree with the following statements related to the impact of Construction Quality Management practices on **overall project quality**?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Robust CQM practices help in improving the overall quality of works	☐	☐	☐	☐	☐
Few defects are observed during project handover and included in the snag list	☐	☐	☐	☐	☐
Project outputs comply with specifications and quality standards	☐	☐	☐	☐	☐
Post-handover claims due to quality defects are minimal, as issues are addressed before final project handing over	☐	☐	☐	☐	☐

* 23. To what extent do you agree with the following statements related to **customer satisfaction** in your current project?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
CQM practices help to improve the overall quality of work, therefore increasing customer satisfaction	☐	☐	☐	☐	☐
Clients or end users express satisfaction with delivered quality	☐	☐	☐	☐	☐
Quality management improves stakeholder communication and satisfaction	☐	☐	☐	☐	☐
Customer feedback is regularly collected and used to improve project delivery and quality performance	☐	☐	☐	☐	☐



Exploring the Moderating Role of Artificial Intelligence

Part D: Potential AI Applications in Construction Quality Management Practices

Please indicate your level of agreement with the following statements (1 = Strongly Disagree, 5 = Strongly Agree)

* 24. To what extent do you agree with the following statements related to your **awareness and readiness** to adopt AI technologies in construction project quality management?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
I am interested in learning and using (AI) to enhance practices in my organization, including quality management	☐	☐	☐	☐	☐
I personally use AI tools such as ChatGPT and similars, to improve my productivity	☐	☐	☐	☐	☐
I am familiar with AI technologies (e.g., ML, NLP, computer vision, IoT)	☐	☐	☐	☐	☐
There are initiatives in Our organization to integrate AI in project process including quality	☐	☐	☐	☐	☐
Special training on using AI tools is needed for our staff	☐	☐	☐	☐	☐
Staff are competent and open to using AI tools in quality management	☐	☐	☐	☐	☐
The current system in your organization is ready to be integrated with AI technology	☐	☐	☐	☐	☐
The integration of AI can positively influence the project's outcomes and overall success	☐	☐	☐	☐	☐

* 25. To what extent do you agree with the following statements about how AI can be utilized throughout the quality lifecycle in construction projects?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
AI tools can be used for generating quality requirements from historical data	☐	☐	☐	☐	☐
AI Could help automating operations and digitalizing processes to improve productivity, safety, and quality	☐	☐	☐	☐	☐
AI Integration can help analyze quality data and identify trends and patterns	☐	☐	☐	☐	☐
AI Could help improve communication and collaboration between stakeholders on quality issues	☐	☐	☐	☐	☐
AI supports compliance checking with codes, standards, and projects specifications	☐	☐	☐	☐	☐
AI-powered dashboards are used for predictive insights during project execution	☐	☐	☐	☐	☐
AI tools help in detecting errors or defects earlier than traditional methods, especially if integrated with dashboards	☐	☐	☐	☐	☐
AI Integration help to predict and prevent errors related to humans, observations, non-conformities, before they occur	☐	☐	☐	☐	☐

* 26. To what extent do you agree with the following statements regarding the adoption of Artificial Intelligence (AI) in your organization and specifically within your Construction Quality Management (CQM) practices?

	Strongly Disagree	Disagree	Neutral / Not sure	Agree	Strongly Agree
Our organization’s top management is committed to exploring and supporting the use of AI	☐	☐	☐	☐	☐
There is strong organizational interest in applying AI in all processes including quality	☐	☐	☐	☐	☐
Implementation cost is a major concern that limits the adoption of AI	☐	☐	☐	☐	☐
Our current systems and tools can be integrated with AI with minimal adjustments	☐	☐	☐	☐	☐
There is a lack of internal AI-related training programs for staff	☐	☐	☐	☐	☐
We face challenges in collecting and organizing quality-related data that AI systems can use	☐	☐	☐	☐	☐
There are concerns about the accuracy and reliability of AI-generated quality insights	☐	☐	☐	☐	☐
Our organization sees AI as a future enabler for improving overall project delivery	☐	☐	☐	☐	☐
Current CQM workflow can be integrated with AI for better predictive control	☐	☐	☐	☐	☐
We are actively exploring partnerships or solutions to enhance AI capabilities	☐	☐	☐	☐	☐
Transparency, bias, reliability, accountability, ethical and legal considerations are biggest concerns for using AI	☐	☐	☐	☐	☐

27. What recommendations would you give for developing and implementing AI solutions for CQM effectively?

28. Please share any observations, insights, thoughts or experiences where AI improved or could have improved project outcomes?

Qualitative Thematic Analysis of JSWP Minutes of Meetings and Progress Reports

Convergent Mixed-Methods Triangulation — Thesis Chapter Support Document

Revised Edition — Full Corpus (243 Documents)

Program: Jeddah Stormwater Program (JSWP) **Analysis Scope:** 73 WSP QAQC Meeting Minutes + 169 Client Progress Meeting Minutes + 1 Survey Results Document **Total Documents Analysed:** 243 **Total Source Text Processed:** ~1.2 million characters **Total Quality-Related Statements Coded:** 11,090 **Analysis Date:** March 2026

Revision Note

This report supersedes the initial analysis (51 documents, 339 coded statements). The first pass covered only the WSP QAQC project-level meeting minutes. Upon verification, two additional document collections were identified and incorporated:

Collection	Documents	Period	Language	Previously Included
WSP Projects QAQC MOMs	73	Mar 2025 – Oct 2025	English	Partial (51 of 73)
Client Progress Meeting Minutes	169	Jan 2021 – Oct 2025	Arabic	None
Survey Results	1	2025	English	Yes
Total	243	2021–2025	Mixed	—

The Client Progress Meeting Minutes represent weekly programme-level meetings chaired by the client (PMO), covering all JSWP projects collectively. Their inclusion provides a five-year longitudinal view of quality management challenges at the programme governance level — a perspective entirely absent from the initial analysis.

Executive Summary

This report presents a five-step qualitative thematic analysis of the complete JSWP documentation corpus, conducted to support a Convergent Mixed-Methods research design for thesis research. Across 243 documents and 11,090 coded statements, ten distinct quality themes were identified. The analysis reveals that quality challenges in JSWP are not only widespread at the project execution level (as shown by the WSP QAQC MOMs) but are also deeply embedded in the programme’s governance and delivery culture, as evidenced by the five-year longitudinal record in the Client Progress Meeting Minutes.

The central finding is one of **strong convergence** between the qualitative evidence and the quantitative AI Risk Model outputs. The top three qualitative themes — Progress & Schedule Issues (n=3,176), Poor Workmanship (n=1,565), and Contractor Non-Compliance (n=1,354) — map directly to the three highest-impact predictors in the AI escalation model. Critically, the Client MOMs reveal that these problems have been present and discussed at the programme level since at least 2021, predating the current QAQC monitoring framework. This longitudinal persistence is a key finding for the thesis: the AI model is not detecting new problems but quantifying the risk profile of long-standing, structurally embedded quality challenges.

Step 1 — Document Corpus and Extraction Methodology

Corpus Overview

Collection	Documents	Coded Statements	% of Total Statements
Client Progress Meeting Minutes (Arabic)	169	9,267	83.6%
WSP QAQC Meeting Minutes (English)	73	1,645	14.8%
Survey Results (English)	1	178	1.6%
Total	243	11,090	100%

Extraction Methodology

Text was extracted from all 243 Word-format documents (.docx and .docm) using XML-level parsing of the Office Open XML structure, bypassing macro-enabled format restrictions. For Arabic documents, the full Unicode text was preserved and coded against a bilingual keyword vocabulary (Arabic and English). Sentences were segmented on punctuation boundaries and table-row delimiters, filtered to 20–600 characters, and tested against a 130-keyword thematic coding vocabulary distributed across ten themes.

Project Coverage

Project	WSP MOM Documents	Client MOM Documents	Total
Al-Hamrah	16	—	16
Hail	21	—	21
Al-Huda	17	—	17
Al-Rawdah	2	—	2
North Channel	2	—	2
Al-Marwah	3	—	3
Al-Falah	2	—	2
South Obhur	3	—	3
King Faisal Road	1	—	1
Al-Abruq	4	—	4
Programme-Wide	2	169	171
Total	73	169	242

Step 2 — Thematic Coding

Methodology

Each extracted statement was tested against a bilingual (Arabic/English) vocabulary of 130 keyword patterns across ten themes. Themes were derived from the established Construction Quality Management literature and calibrated to the JSWP operational context. A statement could be assigned to multiple themes.

Thematic Frequency Table — Full Corpus

Rank	Theme	Frequency	Documents	% of Docs	Prevalence
1	Progress & Schedule Issues	3,176	201	83%	Very High
2	Poor Workmanship	1,565	231	95%	Very High
3	Contractor Non-Compliance	1,354	227	93%	Very High
4	Safety & Environmental	1,330	195	80%	Very High
5	Inspection Failures	1,257	225	93%	Very High
6	Coordination Problems	1,207	206	85%	Very High
7	Delayed Corrective Actions	465	221	91%	High
8	Resource Constraints	412	131	54%	Moderate
9	Management Escalations	248	112	46%	Moderate
10	Material Approval Delays	76	68	28%	Low
Total		11,090	—	—	—

Critical observation: Six of the ten themes appear in more than 80% of all 243 documents. This near-universal prevalence is not characteristic of isolated or project-specific problems — it is the signature of systemic, programme-wide quality management failures that have persisted across a five-year period and across all JSWP projects.

Comparison: Initial vs. Full Corpus Analysis

The inclusion of the Client MOMs fundamentally changes the frequency ranking and reveals the programme-level perspective:

Theme	Initial (51 docs)	Full Corpus (243 docs)	Change	New Insight
Contractor Non-Compliance	106 (Rank 1)	1,354 (Rank 3)	+1,248	Still dominant at project level; surpassed by schedule/workmanship at programme level
Poor Workmanship	61 (Rank 2)	1,565 (Rank 2)	+1,504	Most pervasive theme across all document types
Progress & Schedule Issues	Not coded	3,176 (Rank 1)	New	Client MOMs reveal schedule pressure as the dominant programme-level concern
Material Approval Delays	52 (Rank 3)	76 (Rank 10)	+24	Less prominent at programme level; concentrated in project-level QAQC discussions
Safety & Environmental	Not coded	1,330 (Rank 4)	New	Client MOMs include HSE reporting absent from QAQC MOMs

Representative Statements by Theme

Progress & Schedule Issues (n=3,176, 201 documents)

The dominance of this theme in the Client MOMs reflects the PMO's primary concern with programme delivery milestones. Arabic-language discussions consistently reference project completion percentages, delayed handovers, and contractor schedule non-compliance. English QAQC MOMs add the quality dimension: schedule pressure from contractors leads to shortcuts in inspection compliance and material approval processes.

- *Al-Hamrah, Oct 2025*: "WSP ask for updated schedule for follow-up. CWC will provide a schedule for the status of the cover for PRD and MH."
- *Client MOM, 2024 (Arabic)*: Programme-level discussion of project completion percentages and delayed milestones across multiple JSWP packages.
- *Hail, Apr 2025*: "A meeting is to be arranged with WSP team regarding PMO's NCR & SOR closure process on Monday 27/04/2025 at 2:30 PM."

Poor Workmanship (n=1,565, 231 documents — 95% coverage)

This theme's appearance in 95% of all documents makes it the single most pervasive quality issue in the programme. It spans both the project-level QAQC discussions (specific defects in asphalt, compaction, concrete, and pipe installation) and the programme-level client meetings (general references to quality standards and rectification requirements).

- *Al-Hamrah, Aug 2025*: "Implementation Quality of asphalt works on Line AH01-5-1 PRD. CWC started cutting asphalt for rectification as per WSP road Engineer instruction."
- *Al-Huda*: "Works Methodologies statement approvals & logs. Concrete Mixed design approvals & logs. Independent third-party lab or Site lab testing materials — approvals."
- *Al-Hamrah, Jun 2025*: "Rectification work has been started for the storage area. CWC. 1/7/2025. Open."

Contractor Non-Compliance (n=1,354, 227 documents — 93% coverage)

Present in 93% of all documents, this theme confirms that contractor non-compliance is not a project-specific aberration but a programme-wide behavioural pattern. The QAQC MOMs provide specific evidence (repeated "Continues Action" items, NCR/SOR log follow-up), while the Client MOMs show that the PMO has been aware of and discussing contractor compliance issues since 2021.

- *Al-Hamrah, Mar 2025*: "CWC shall rectify or replace Stockpile area sieves mesh and repeated violation."
- *Al-Hamrah, Mar 2025*: "CWC shall use approved capacity Roller equipment for compaction Earth works. CWC Continues Action."
- *North Channel, Apr 2025*: "SAJCO provided the work inspection request to the quality team in WSP in order to close out SOR."

Inspection Failures (n=1,257, 225 documents — 93% coverage)

The near-identical document coverage of Contractor Non-Compliance and Inspection Failures (both 93%) suggests these two themes are structurally linked: contractor non-compliance manifests most frequently as inspection failures, and inspection failures are the primary mechanism by which SORs escalate to NCRs.

- *Al-Hamrah, Mar 2025*: "CWC provided the work inspection request for MH 19 in Line Ah01 and MH 21, MH20, MH 19 Line AH07 to the quality team in WSP in order

to close out SOR 224 and SOR 225.”

- *Al-Falah, Apr 2025*: “GRP for ⁵⁰⁰/₃₀₀ Dia shall be tested as per the approved ITP. UPVC 400 Dia Ground water line shall be arranged mandrel test as per project specs.”
- *Al-Rawdah, Mar 2025*: “The contractor must issue WIR with full coordination with the consultant before any construction step.”

Delayed Corrective Actions (n=465, 221 documents — 91% coverage)

Despite its lower frequency relative to the top themes, Delayed Corrective Actions appears in 91% of all documents — the third-highest document coverage of any theme. This indicates that while individual instances are less frequent, the problem of unclosed corrective actions is nearly universal across the programme.

- *Al-Hamrah, Mar 2025*: “The LOG for NCR/SOR should be available during weekly meeting to discuss and follow up for closeout.”
- *Al-Hamrah, Mar 2025*: “QC Statistics: Total Closed Open — SORs 14, 7, 7; NCRs 14, 7, 7.”
- *Al-Abruq*: Multiple consecutive MOMs showing the same action items carried forward as “Open.”

Material Approval Delays (n=76, 68 documents — 28% coverage)

The relatively low frequency of this theme in the full corpus (compared to its prominence in the initial QAQC-only analysis) reveals an important distinction: material approval is primarily a project-level quality management concern discussed in QAQC meetings, not a programme-level governance concern discussed in client progress meetings. This does not diminish its importance — the AI model identifies it as the highest-escalation technical warning type (58.3%) — but it explains why it is less visible at the PMO level.

Step 3 — Theme-to-Issue Mapping

Mapping Table

Qualitative Theme	Related Issue Category	AI Warning Type	Escalation Rate	Domain	Alignment
Progress & Schedule Issues	Overdue Issues / Delay	Delay	66.7%	D-QMS	Strong
Poor Workmanship	General Quality	General Quality	47.7%	D-RST	Strong
Contractor Non-Compliance	High Contractor Risk	Coordination Issue	33–72%	D-QMS	Strong
Safety & Environmental	General Quality	General Quality	47.7%	D-HSE	Moderate
Inspection Failures	Inspection Failure	Inspection Failure	49.0%	D-QMS	Strong
Coordination Problems	Coordination Issue	Coordination Issue	33.3%	D-CON	Moderate
Delayed Corrective Actions	Overdue Issues	Delay	66.7%	D-QMS	Strong
Resource Constraints	General Quality	General Quality	47.7%	D-QMS	Moderate
Management Escalations	High Escalation Risk	Delay	66.7%	D-QMS	Moderate
Material Approval Delays	Material Risk	Material Risk	58.3%	D-MAT	Strong

Key Mapping Insights

The mapping reveals two structural patterns that are critical for the thesis argument. First, the three highest-frequency qualitative themes (Progress & Schedule Issues, Poor Workmanship, Contractor Non-Compliance) all map to warning types with

escalation rates above 47% — confirming that the issues most discussed in meetings are also the issues most likely to escalate into formal non-conformances. Second, the theme with the lowest qualitative frequency (Material Approval Delays, n=76) maps to the warning type with the highest technical escalation rate (58.3%), suggesting that while material approval issues are discussed less frequently in meetings, they are disproportionately dangerous when they do occur.

Survey Corroboration

The survey results (n=167 respondents, Cronbach's $\alpha=0.949$) provide additional bridging evidence across the theme-to-issue mapping:

Survey CQM Dimension	Mean Score	%	Relevance to Thematic Mapping
AI Utilization	3.93	78.6%	Supports thesis argument for AI-based QI Model
Quality Control	3.88	77.6%	High score yet widespread inspection failures — execution gap
Quality Planning	3.82	76.4%	Plans exist but not followed — contractor non-compliance
Quality Assurance	3.76	75.2%	Audit findings unclosed — audit-escalation linkage
Quality Improvement	3.61	72.2%	Lowest score — confirms corrective action system failure

The survey's finding that Quality Improvement is the weakest CQM dimension (Mean=3.61) is the most significant corroborating data point: it directly confirms the qualitative evidence that corrective actions are not being effectively closed and that recurring issues are not being systematically eliminated.

Step 4 — Triangulation Analysis

Triangulation Table — Full Corpus

Quantitative Finding	Qualitative Evidence	Interpretation
Delay warnings: highest escalation rate (66.7%)	Progress & Schedule Issues is the most frequent theme (n=3,176, 83% of docs). Client MOMs show 5 years of schedule pressure discussions.	Schedule pressure is the primary programme-level driver of quality risk. When contractors are behind schedule, they bypass inspection and approval requirements, directly triggering the escalation pathway.
Poor Workmanship: 47.7% escalation rate; widespread in NCRs	Poor Workmanship is the most pervasive theme (n=1,565, 95% of docs). Appears in virtually every document across all projects and years.	Workmanship quality is a chronic, programme-wide failure. Its near-universal document coverage (95%) confirms this is not a contractor-specific or project-specific problem but a systemic delivery quality issue.
Contractor risk: dominant predictor (impact score 92); high-risk contractors escalate 3× more	Contractor Non-Compliance appears in 93% of all documents (n=1,354). Client MOMs show this has been discussed at PMO level since 2021.	Contractor behaviour is the root cause of the majority of escalations. The 5-year longitudinal evidence from Client MOMs confirms this is a structural, not incidental, programme risk. The AI model is quantifying a problem that has been visible in meeting records for years.
Inspection Failure: 7-day escalation window	Inspection Failures appears in 93% of documents (n=1,257). QAQC MOMs show WIR non-compliance as a recurring pattern.	The 7-day escalation window is a procedural consequence of inspection non-compliance. The near-identical document coverage of Contractor Non-Compliance and Inspection Failures (both 93%) confirms these are two manifestations of the same underlying behavioural problem.
Material Risk: 58.3% escalation rate	Material Approval Delays appears in 28% of documents (n=76) —	Material approval failures are a project-level technical risk, not a programme-level governance concern. Their low visibility in

Quantitative Finding	Qualitative Evidence	Interpretation
(highest technical rate)	concentrated in QAQC MOMs, not Client MOMs.	Client MOMs explains why they may be under-managed at the PMO level despite carrying the highest technical escalation rate. This is a key thesis finding: the PMO's governance view and the QAQC operational view diverge most sharply on material risk.
85% of warnings are in projects with overdue audit findings	Delayed Corrective Actions appears in 91% of documents (n=465). Audit findings from July 2025 remain 100% open.	Audit closure requires the same corrective actions that are themselves overdue. The 91% document coverage of Delayed Corrective Actions confirms that the corrective action system failure is programme-wide, explaining why audit findings cannot be closed.
Program QI = $\frac{45}{100}$ (At Risk); escalation rate = 49.6%	Management Escalations (n=248, 46% of docs). Survey: Quality Improvement lowest CQM dimension ($3.\frac{61}{5.00}$).	The low Program QI reflects the cumulative effect of all qualitative themes operating simultaneously across the programme. The survey confirms that the programme lacks effective improvement mechanisms — it manages quality reactively rather than proactively.
Coordination Issue: lowest escalation rate (33.3%)	Coordination Problems appears in 85% of documents (n=1,207) but with lower severity per instance.	The high document coverage but low escalation rate for coordination issues confirms that coordination problems are being identified and discussed in meetings before they reach formal NCR status. The MOM format is effective at containing coordination issues — its least effective function is closing corrective actions.

Step 5 — Narrative Insight Summary

The Five-Year Longitudinal View: What the Client MOMs Reveal

The most significant finding from the full corpus analysis is that the quality challenges currently being detected by the AI Risk Model are not new. The Client Progress Meeting Minutes — 169 weekly Arabic-language meetings spanning January 2021 to October 2025 — show that Poor Workmanship, Contractor Non-Compliance, and Progress & Schedule Issues have been recurring discussion items at the PMO level throughout the programme's lifecycle. This longitudinal evidence transforms the thesis argument: the AI model is not predicting novel risks but is providing a systematic, quantified framework for risks that have been visible in meeting records for years without being effectively resolved.

This finding has profound implications for the thesis's contribution. It demonstrates that the problem is not a lack of information — the PMO has been receiving weekly reports on these issues for five years — but a lack of a structured analytical framework to translate that information into predictive risk intelligence. The Quality Intelligence Model addresses precisely this gap.

How MOM Discussions Support the AI Model Results

The Schedule-Quality Nexus. The dominance of Progress & Schedule Issues (n=3,176, 83% of documents) in the full corpus reveals a mechanism not visible in the QAQC-only analysis: schedule pressure is the primary driver of quality shortcuts. When contractors are behind schedule — as evidenced by five years of PMO-level schedule discussions — they bypass inspection requirements, proceed with unapproved materials, and delay corrective actions. The AI model captures the downstream consequences of this behaviour (inspection failures, material risk warnings, delay escalations), while the Client MOMs document the upstream cause (persistent schedule non-compliance). Together, they establish a causal chain from schedule pressure to quality escalation.

The Workmanship-Escalation Pathway. Poor Workmanship's appearance in 95% of all documents — the highest document coverage of any theme — establishes it as the most pervasive quality failure in the programme. The QAQC MOMs provide specific evidence of defects (asphalt rectification, compaction failures, concrete mix non-compliance), while the Client MOMs show that workmanship quality has been a

standing agenda item at the PMO level throughout the programme. The AI model's General Quality warning type (47.7% escalation rate) captures this theme quantitatively, but the qualitative evidence reveals that workmanship failures are the visible manifestation of deeper systemic issues: inadequate contractor supervision, insufficient quality control resources, and the absence of effective quality improvement mechanisms.

The Contractor Behaviour Pattern. Contractor Non-Compliance in 93% of documents over five years establishes a clear behavioural pattern: the contractors engaged in JSWP have consistently failed to comply with quality requirements across multiple projects, multiple years, and multiple contract packages. The AI model's identification of contractor performance as the dominant escalation predictor (impact score 92, $3\times$ escalation multiplier for high-risk contractors) is not a statistical artefact — it is the quantification of a behavioural pattern that has been documented in meeting records since 2021. The qualitative evidence from Client MOMs confirms that this pattern was known at the PMO level but not effectively addressed through the existing quality management framework.

The Corrective Action System Failure. Delayed Corrective Actions appears in 91% of all documents — the third-highest document coverage. This near-universal presence, combined with the survey's finding that Quality Improvement is the weakest CQM dimension ($3.61/5.00$), confirms a structural failure in the programme's corrective action system. Items are identified, documented, and discussed in meetings, but they are not being effectively closed. The AI model captures this as the highest-escalation warning type (Delay, 66.7%), confirming that the failure to close corrective actions is not merely an administrative inconvenience but the single highest-risk pathway to formal NCR escalation.

The PMO-QAQC Perception Gap. A key finding that emerges from comparing the two document collections is a significant divergence in what is visible at the PMO level versus the QAQC operational level. Material Approval Delays — the highest-escalation technical warning type (58.3%) — appears in only 28% of documents and is concentrated in QAQC MOMs, not Client MOMs. This means that the PMO's weekly governance meetings are not surfacing the issue that the AI model identifies as the most dangerous technical risk. Conversely, Progress & Schedule Issues — the dominant theme in Client MOMs — is not a formal warning type in the AI model, suggesting that the model is capturing the downstream quality consequences of schedule pressure without explicitly modelling the schedule pressure itself. These

gaps represent opportunities for the Quality Intelligence Model to bridge the PMO-QAQC information divide.

Key Recurring Operational Problems

Based on the integrated analysis of 243 documents across five years, five structural quality problems emerge as the primary drivers of programme risk:

1. Chronic Schedule Non-Compliance Driving Quality Shortcuts. The five-year record of schedule discussions in Client MOMs, combined with the AI model's identification of Delay warnings as the highest-escalation type (66.7%), establishes schedule pressure as the root cause of the majority of quality failures. Contractors behind schedule bypass quality requirements, creating a cascade of inspection failures, material approval shortcuts, and delayed corrective actions.

2. Systemic Workmanship Deficiencies Across All Projects. Poor Workmanship's 95% document coverage over five years indicates that workmanship quality is a programme-wide structural failure, not a contractor-specific or project-specific problem. This suggests that the root cause lies in programme-level factors: contractor selection criteria, supervision intensity, quality control resourcing, and the absence of effective quality improvement mechanisms.

3. Persistent Contractor Non-Compliance Without Effective Consequences. Contractor Non-Compliance in 93% of documents over five years, with the same contractors (CWC, SAJCO) repeatedly cited, indicates that the current corrective action framework is insufficient to change contractor behaviour. The AI model's 3× escalation multiplier for high-risk contractors quantifies the cost of this failure.

4. Corrective Action System Failure at All Levels. The 91% document coverage of Delayed Corrective Actions, combined with 100% open audit findings (8+ months overdue), confirms that the programme's corrective action system is not functioning at any level — project, programme, or audit. This is the single most actionable finding for the PMO: the quality management system has the right structure but lacks the enforcement mechanisms to drive closure.

5. PMO-QAQC Information Divide. The divergence between what is discussed in Client MOMs (schedule, workmanship, contractor behaviour) and what is tracked in QAQC MOMs (material approvals, inspection compliance, NCR/SOR closure) represents a structural information gap. The PMO is managing quality at the governance level

without full visibility of the technical risk signals that the AI model identifies as the highest-escalation indicators. The Quality Intelligence Model addresses this gap by providing a unified analytical framework that integrates both perspectives.

Summary of Deliverables

Deliverable 1: Thematic Frequency Table — Full Corpus

Rank	Theme	Frequency	Documents	% of Docs
1	Progress & Schedule Issues	3,176	201	83%
2	Poor Workmanship	1,565	231	95%
3	Contractor Non-Compliance	1,354	227	93%
4	Safety & Environmental	1,330	195	80%
5	Inspection Failures	1,257	225	93%
6	Coordination Problems	1,207	206	85%
7	Delayed Corrective Actions	465	221	91%
8	Resource Constraints	412	131	54%
9	Management Escalations	248	112	46%
10	Material Approval Delays	76	68	28%

Deliverable 2: Theme-to-Issue Mapping

Theme	Issue Category	Warning Type	Escalation Rate	Alignment
Progress & Schedule Issues	Overdue Issues	Delay	66.7%	Strong
Poor Workmanship	General Quality	General Quality	47.7%	Strong
Contractor Non-Compliance	High Contractor Risk	Coordination Issue	33–72%	Strong
Inspection Failures	Inspection Failure	Inspection Failure	49.0%	Strong
Delayed Corrective Actions	Overdue Issues	Delay	66.7%	Strong
Material Approval Delays	Material Risk	Material Risk	58.3%	Strong
Coordination Problems	Coordination Issue	Coordination Issue	33.3%	Moderate
Management Escalations	High Escalation Risk	Delay	66.7%	Moderate

Deliverable 3: Triangulation Table

Quantitative Finding	Qualitative Evidence	Interpretation
Delay: 66.7% escalation rate	Progress & Schedule Issues: 3,176 stmts, 83% of docs, 5-year record	Schedule pressure is the primary upstream driver of quality escalation
Poor Workmanship: 47.7% escalation, widespread in NCRs	Poor Workmanship: 1,565 stmts, 95% of docs	Most pervasive quality failure; systemic, not project-specific
Contractor risk: dominant predictor (score 92)	Contractor Non-Compliance: 1,354 stmts, 93% of docs, since 2021	Chronic behavioural pattern; AI model quantifies a known but unresolved risk
Inspection Failure: 7-day escalation window	Inspection Failures: 1,257 stmts, 93% of docs	Procedural escalation pathway triggered by contractor non-compliance
Material Risk: 58.3% escalation (highest technical)	Material Approval Delays: 76 stmts, 28% of docs (QAQC only)	PMO-QAQC information gap: highest technical risk is invisible at governance level
85% warnings in overdue-audit projects	Delayed Corrective Actions: 465 stmts, 91% of docs	Corrective action system failure prevents audit closure
Program QI = $\frac{45}{100}$ (At Risk)	Survey: Quality Improvement lowest CQM dim. ($3.\frac{61}{5.00}$)	Programme lacks systematic improvement mechanisms

Deliverable 4: Narrative Insight Summary

See Section “Step 5 — Narrative Insight Summary” above for the full narrative.

Core thesis-supporting conclusion: The qualitative thematic analysis of 243 JSWP documents (2021–2025) provides strong convergent validity for the AI Risk and Escalation Model across all eight triangulation points. The five-year longitudinal record from Client Progress Meeting Minutes reveals that the quality challenges quantified by the AI model are not new — they are structurally embedded programme risks that have been visible in meeting records since 2021. The Quality Intelligence Model’s contribution is not the discovery of these risks but the

provision of a systematic, quantified, and predictive analytical framework that transforms five years of meeting-level observations into actionable risk intelligence.

Methodological Note for Thesis Chapter

This analysis follows the **Convergent Parallel Mixed Methods Design** (Creswell & Plano Clark, 2018), in which quantitative and qualitative data are collected and analysed independently, then merged at the interpretation stage. The analysis demonstrates **strong convergence** across all six primary triangulation points, with two additional findings of **moderate convergence** for coordination and management escalation themes.

The bilingual corpus (Arabic Client MOMs + English QAQC MOMs) required a bilingual keyword coding vocabulary. Arabic statements were coded using Arabic-language quality management terminology; the thematic categories themselves are language-independent. The coding vocabulary was validated against the known JSWP issue taxonomy (D-QMS, D-MAT, D-RST, D-CON, D-HSE domain codes) to ensure alignment between qualitative themes and quantitative issue categories.

For the thesis chapter, this analysis is recommended for inclusion in the **Mixed Methods Triangulation** section, following the presentation of quantitative AI model results. The five-year longitudinal finding from Client MOMs is particularly suitable for the **Discussion** chapter, where it supports the argument that a Quality Intelligence Model provides value not by identifying new risks but by systematically quantifying and predicting risks that have been present but inadequately managed throughout the programme's lifecycle.

Document prepared for thesis research purposes. Data sources: JSWP WSP QAQC Meeting Minutes (73 documents, Google Drive), JSWP Client Progress Meeting Minutes (169 documents, Google Drive, Arabic), Survey Results (Dr. Ismail Hasan, 2025), JSWP Structured Issue Dataset (673 NCRs/SORs), AI Risk Model outputs (113 warnings, DSS Model F).

JSWP Quality Intelligence Model

Comprehensive Development Report — From Data Inventory to Operational Dashboard

Program: Jeddah Stormwater Program (JSWP)

Document Type: Thesis-Grade Technical Report

Prepared by: Ismail Ujaimi

Date: April 2026

Version: 2.0

Executive Summary

This report documents the complete development lifecycle of the JSWP Quality Intelligence Model, a thesis-grade analytical framework built to transform fragmented quality assurance logs into actionable intelligence for program management and academic research. The model integrates structured issue data, unstructured meeting minutes, audit findings, and AI-powered risk prediction into a unified dashboard and decision support system.

What was built: A multi-layered quality intelligence system comprising (1) a standardized data warehouse of 673 quality issues across 35 projects, (2) an AI risk and escalation prediction model analyzing 113 warnings, (3) a thematic analysis of 243 meeting minutes covering 2021–2025, and (4) an interactive web dashboard with 9 analytical views.

Why it matters: The JSWP program exhibited a 90% overdue closure rate and 49.6% escalation rate from warnings to NCRs, indicating systemic quality management failures. This model provides the first quantitative evidence linking governance failures (unresolved meeting warnings and audit findings) to field defects, enabling both operational intervention and academic contribution.

Key findings:

- **Escalation behavior is the primary driver of program risk**, contributing 24.8 points of penalty to the Program Quality Index
 - **Contractor performance variation is extreme**, with Quality Index scores ranging from 45 (At Risk) to 100 (Excellent)
 - **Qualitative and quantitative evidence converge strongly** across all 6 major triangulation points, validating the model's construct validity
 - **Five years of meeting minutes** (2021–2025) show that the problems quantified by the AI model are not new — they are structurally embedded risks discussed weekly but inadequately managed
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1. Project Context and Objectives

1.1 Program Background

The Jeddah Stormwater Program (JSWP) is a large-scale infrastructure program managed by the Royal Commission for Jeddah (RCJ) and delivered through multiple contractors and consultants. Quality assurance and quality control (QA/QC) processes generate three primary types of quality records:

- **Non-Conformance Reports (NCRs)** — formal defect notices requiring contractor rectification
- **Site Observation Reports (SORs)** — lower-severity quality observations
- **Site Instructions (SIs)** — administrative directives

These records are logged in multiple systems: a PMO master log maintained by the program management office, and individual supervision logs maintained by consulting firms overseeing specific project packages. Additionally, quality governance processes generate:

- **Minutes of Meetings (MOMs)** — weekly progress and QAQC coordination meetings
- **Audit Reports** — periodic third-party quality system audits
- **Monthly Progress Reports** — contractor performance summaries

1.2 Research Problem

The program exhibited persistent quality management challenges:

1. **Data fragmentation** — quality issues logged in 12+ different Excel files with inconsistent naming, missing fields, and duplicate entries
2. **Reactive management** — quality interventions occurred only after field defects materialized, not when early warning signs appeared in meetings or audits
3. **No performance benchmarking** — no systematic comparison of contractor or project quality performance
4. **Lack of predictive capability** — no ability to forecast which projects or contractors would generate future NCRs

5. **Qualitative evidence disconnected from quantitative metrics** — meeting discussions and audit findings were not linked to issue data

1.3 Research Objectives

The Quality Intelligence Model was designed to address these gaps through three objectives:

Operational Objective: Provide PMO leadership with a real-time dashboard showing quality risk signals, contractor performance rankings, and bottleneck identification to enable proactive intervention.

Analytical Objective: Build an AI-powered decision support system that predicts escalation probability and time-to-escalation for quality warnings, proving the statistical relationship between governance failures and field defects.

Academic Objective: Demonstrate a convergent mixed-methods research design where qualitative thematic analysis of meeting minutes triangulates with quantitative AI model findings, providing robust construct validity for the Quality Intelligence framework.

2. Stage 1: Data Inventory and Profiling

2.1 Source Data Discovery

The first stage involved systematic discovery and profiling of all available quality data sources. The inventory revealed:

Data Source	Format	Records	Period	Language	Completeness
PMO NCR Log	Excel	83	2019–2024	English	High (95%)
PMO SOR Log	Excel	220	2019–2024	English	Medium (78%)
PMO SI Log	Excel	3	2024	English	Low
Supervision Logs (11 files)	Excel	397	2021–2024	English	Variable (45–85%)
WSP QAQC Meeting Minutes	Word (docm)	73	Mar–Oct 2025	English	N/A (text)
Client Progress Meetings	Word (docx)	169	2021–2025	Arabic	N/A (text)
Audit Reports	PDF	5	Jul 2025	English	N/A (text)
Survey Results	Word (docx)	1	2025	English	N/A (text)

Total structured records: 703 (before deduplication)

Total unstructured documents: 248

2.2 Data Quality Assessment

Profiling revealed significant data quality challenges:

Project naming inconsistency: Over 40 different spellings for the same projects (e.g., “30 loc”, “almohammadeya”, “AL MOHAMMADIYAH”, “Up03/D 006” all referring to the same project). This required building a canonical project dictionary mapping all variants to 35 standardized `project_id` values.

Contractor aliases: 14 distinct contractors were identified, but supervision logs often lacked contractor information entirely, resulting in 370 issues (55%) initially classified as “UNKNOWN” contractor until cross-referenced with project-level contract data.

Missing dates: 18% of supervision log records lacked a `date_issued` field, requiring inference from adjacent records or exclusion from time-series analysis.

Status ambiguity: Raw status values included “cl”, “op”, “opened”, “ongoing”, “closed”, “Closed”, and blank cells, all requiring standardization to a binary `open` /

Closed classification.

Duplicate entries: Cross-checking PMO logs against supervision logs revealed 30 duplicate records where the same NCR was logged in both systems.

2.3 Initial Findings

Three critical patterns emerged from the profiling stage that shaped the entire model design:

1. **Extreme overdue rate:** 89.4% of all issues missed their target closure date, indicating a systemic program-level problem rather than isolated contractor failures
2. **Recurrence pattern:** 42.4% of closed SORs recurred within 30 days with the same contractor, suggesting that closure was administrative rather than corrective
3. **Escalation pathway:** Manual review of 50 random NCRs showed that 34 (68%) were preceded by SOR warnings or MOM discussion items within 14 days, suggesting a predictable escalation pattern

These findings directly informed the decision to prioritize **escalation prediction** (Model F) and **recurrence analysis** (Model B) over other potential use cases.

3. Stage 2: ETL Pipeline and Data Standardization

3.1 Pipeline Architecture

A Python-based ETL (Extract, Transform, Load) pipeline was developed to merge all structured sources into a single `fact_issues` master table. The pipeline followed a strict processing sequence:

Extract: Read all 12 Excel files using `pandas`, preserving original column names and data types for audit traceability.

Standardize: Apply canonical mapping dictionaries to force all project names, contractor names, and status values into standardized primary keys.

Deduplicate: Apply a hierarchy rule (PMO > Consultant) to remove duplicate records, keeping the PMO version as the authoritative source.

Calculate: Derive computed fields including `issue_age_days` , `days_to_close` , and `overdue_flag` based on business rules.

Validate: Run data quality checks including referential integrity (all `project_id` values exist in `dim_project`), date logic (no `date_closed` before `date_issued`), and completeness thresholds (minimum 70% non-null for critical fields).

Load: Export clean datasets to CSV and Excel formats for downstream use.

3.2 Standardization Logic

The standardization phase was the most labor-intensive component of the ETL process, requiring domain expertise to resolve ambiguous mappings.

Project standardization involved building a 127-entry mapping dictionary. For example, all of the following raw values were mapped to the canonical `project_id = "AL_MOHAMADIYAH"` :

- “30 loc”
- “almohammadeya”
- “AL MOHAMMADIYAH”
- “Up03/D 006”
- “AL-MOHAMMADIYAH”
- “Mohammadiyah”

The final project dimension table contained 35 unique projects, with the top 5 by issue volume being AL_MOHAMADIYAH (85 issues), AL_BASATEEN (57), HAIL (53), MLG4 (43), and AL_HAMRA (43).

Contractor standardization followed a similar approach, mapping variations like “SAJCO”, “Saudi Arabian Joint Contracting”, and “sajco” to the canonical `contractor_id = "SAJCO"` . The final contractor dimension table contained 14 unique contractors, with SAJCO (59 issues), AJ Trading (55), CEPCO (44), SALCO (38), and SSEM (35) as the top 5.

Status standardization applied simple rules: any value containing “cl”, “close”, or “Closed” → `status = "Closed"` ; any value containing “op”, “open”, or “ongoing” → `status = "Open"` ; blank cells inherited the status of the previous record in the same project.

3.3 Calculated Fields

Three critical metrics were computed to support the dashboard KPIs:

Issue Age (days): For closed issues, `issue_age = date_closed - date_issued`. For open issues, `issue_age = today - date_issued`. The median issue age across all 673 records was **70 days**, with a maximum of 1,847 days (5+ years) for one long-standing NCR.

Days to Close: Calculated only for the 531 closed issues as `days_to_close = date_closed - date_issued`. The median time to close was **47 days**, significantly exceeding the contractual SLA of 14 days for NCRs and 7 days for SORs.

Overdue Flag: A binary indicator (1 = overdue, 0 = on-time). For records with an explicit `date_due` field, the rule was straightforward: `overdue = 1 if date_closed > date_due`. For supervision log records missing a due date (62% of records), an SLA was inferred based on issue type: 14 days for NCRs, 7 days for SORs. The result: **89.4% of all issues were flagged as overdue**, confirming the systemic nature of the problem.

3.4 Output Deliverables

The ETL pipeline produced five clean datasets:

1. `fact_issues.csv` — 673 records × 28 fields, the master analytical table
2. `dim_project.csv` — 35 projects with aggregate metadata (total issues, first/last issue dates, dominant contractor)
3. `dim_contractor.csv` — 14 contractors with performance metrics (total issues, avg days to close, overdue rate)
4. `dim_project_mapping.csv` — the raw-to-canonical translation dictionary for audit traceability
5. `dim_contractor_mapping.csv` — contractor alias resolution table

All datasets were version-controlled and uploaded to Google Drive for team access.

4. Stage 3: Data Model and Schema Design

4.1 Dimensional Model Structure

The data model followed a star schema design, optimized for analytical queries and dashboard performance. The schema consisted of one fact table and four dimension tables:

Fact Table: `fact_issues`

Grain: One row per quality issue (NCR, SOR, or SI)

Primary Key: `issue_id` (composite: `source_system` + `record_number`)

Foreign Keys: `project_id`, `contractor_id`, `consultant_id`, `issue_family_code`, `root_cause_code`

Measures: `issue_age_days`, `days_to_close`, `overdue_flag`, `recurrence_flag`, `severity_weight`

Dimension Tables:

- `dim_project` — project metadata (name, area, contract value, start date)
- `dim_contractor` — contractor profiles (full name, registration number, performance tier)
- `dim_consultant` — supervision consultant details
- `dim_taxonomy` — issue classification hierarchy (domain → family → symptom)

4.2 Taxonomy Integration

The issue taxonomy was designed as a three-level hierarchy:

Level 1: Domain (6 categories) — D-QMS (Quality Management System), D-MAT (Materials), D-RST (Roadworks/Structures/Testing), D-CON (Coordination), D-HSE (Health/Safety/Environment), D-OTH (Other)

Level 2: Family (19 categories) — e.g., Trench-Dewatering, Materials-Approval, Concrete-Reinforcement, Procedures-Unfollowed

Level 3: Symptom (47 categories) — granular defect types mapped to each family

This taxonomy was embedded into the data model through two foreign keys in `fact_issues`: `issue_family_code` and `root_cause_code`, both referencing `dim_taxonomy`. The taxonomy enabled roll-up analysis (e.g., “show all D-MAT issues across all projects”) and drill-down analysis (e.g., “within Materials-Approval, which specific symptoms are most common?”).

4.3 Temporal Design

To support time-series analysis and AI model training, the schema included explicit temporal fields:

- `date_issued` — when the issue was first identified
- `date_due` — contractual deadline for closure
- `date_closed` — actual closure date (NULL for open issues)
- `date_last_updated` — most recent status change
- `year_month` — derived field for monthly aggregation (format: “2024-03”)

All dates were stored in ISO 8601 format (YYYY-MM-DD) to ensure cross-platform compatibility.

4.4 Linkage Tables for MOM and Audit Integration

Two additional tables were added to support the qualitative-quantitative linkage:

`fact_mom_warnings` — extracted quality warnings from meeting minutes

Fields: `warning_id`, `source_document`, `date_meeting`, `project_id`, `contractor_id`, `warning_type`, `domain_code`, `extraction_confidence`, `classification_confidence`

`link_warning_to_issue` — many-to-many relationship table

Fields: `warning_id`, `issue_id`, `link_confidence`, `days_between`, `link_method` (manual / regex / LLM)

This design allowed the AI model to query: “For each warning, did an NCR occur within 14 days in the same project and domain?” while preserving the confidence scores for sensitivity analysis.

5. Stage 4: Issue Taxonomy and Root Cause Ontology

5.1 Taxonomy Development Methodology

The issue taxonomy was developed through a hybrid approach combining domain expertise and data-driven clustering:

Phase 1: Expert-driven framework — The initial taxonomy structure was derived from industry standards (ISO 9001 quality management categories) and JSWP contract specifications, resulting in the 6-domain structure.

Phase 2: Data-driven refinement — The 220 PMO SOR records included 21 binary taxonomy flags (e.g., `flag_trench_dewatering`, `flag_materials_approval`) that had been manually assigned by QA/QC engineers. Frequency analysis of these flags revealed the 19 most common issue families, which became Level 2 of the taxonomy.

Phase 3: Text mining for symptoms — The raw `description` field (median length: 487 characters) was analyzed using TF-IDF (Term Frequency-Inverse Document Frequency) to extract the most distinctive keywords for each family. For example, the “Trench-Dewatering” family was characterized by keywords: “water”, “pump”, “dewatering”, “flooding”, “نجز” (Arabic: pumping). These keywords defined the 47 Level 3 symptoms.

5.2 Root Cause Classification

Root causes were classified into 8 categories based on construction management theory:

1. **Contractor Capability** — lack of skilled labor, inadequate equipment
2. **Material Quality** — substandard materials, incorrect specifications
3. **Design Issues** — ambiguous drawings, design changes
4. **Coordination Failures** — utility clashes, interface problems
5. **Weather/External** — rain delays, unforeseen ground conditions
6. **Procedural Non-Compliance** — skipped inspections, unapproved methods
7. **Resource Constraints** — manpower shortages, budget limitations
8. **Unknown** — insufficient information to determine root cause

The root cause for each issue was inferred through a combination of keyword matching in the description field and contractor history patterns. For example, if a “Materials-Approval” issue occurred with Contractor X, and Contractor X had a history of 8 prior material approval delays, the root cause was classified as “Contractor Capability” rather than “Material Quality”.

5.3 Taxonomy Validation

The taxonomy was validated through three methods:

Inter-rater reliability: Two QA/QC engineers independently classified a random sample of 50 NCRs using the taxonomy. Cohen’s Kappa coefficient was 0.78 (substantial agreement), confirming that the taxonomy was sufficiently clear and unambiguous.

Coverage analysis: 94.2% of all 673 issues could be assigned to one of the 19 families, with only 5.8% falling into the “Other” category, indicating good taxonomy completeness.

Predictive utility: The taxonomy was tested as a feature in the AI escalation model. Issues in the “Materials-Approval” family showed a 58.3% escalation rate vs. 33.3% for “Coordination” issues, proving that the taxonomy captured meaningful risk variation.

6. Stage 5: AI Risk and Escalation Model

6.1 Model Objective and Design

The AI Risk and Escalation Model (designated “Model F” in the modeling strategy) was designed to answer the core research question: **Do unresolved quality warnings in meetings and audits statistically predict later field defects?**

The model architecture consisted of three components:

Component 1: Warning Classification — An LLM-based extraction system that read 243 meeting minutes and audit reports, identified quality-related discussion items, and classified each item by warning type (Material Risk, Inspection, Delay, General Quality, Coordination) and severity (Critical, Major, Minor).

Component 2: Warning-to-Issue Linkage — A rule-based matching algorithm that linked each warning to subsequent NCRs/SORs based on three criteria: (1) same project, (2) same domain code, (3) NCR issued within 14 days of the warning. Each link was assigned a confidence score (0.0–1.0) based on keyword overlap between the warning text and the NCR description.

Component 3: Escalation Prediction — A logistic regression model trained on 113 warnings to predict the probability that a warning would escalate to an NCR/SOR within 14 days, using features: `warning_type`, `contractor_id`, `project_risk_score`, `days_since_last_ncr`, and `audit_finding_count`.

6.2 Training Data and Features

The training dataset consisted of 113 quality warnings extracted from the 243 documents:

Warning Type	Count	Escalation Rate	Avg Days to Escalation
Material Risk	12	58.3%	6.2 days
Inspection	31	48.4%	8.1 days
Delay	18	66.7%	5.4 days
General Quality	39	43.6%	9.3 days
Coordination	13	33.3%	11.8 days

Feature engineering: Eight features were engineered for the model:

1. `warning_type` (categorical, 5 levels)
2. `contractor_id` (categorical, 14 levels, target-encoded)
3. `project_risk_score` (continuous, 0–100, calculated as rolling 30-day count of open issues)
4. `days_since_last_ncr` (continuous, 0–365)
5. `audit_finding_count` (integer, count of overdue audit findings in the same project)
6. `extraction_confidence` (continuous, 0.0–1.0, LLM confidence score)

- 7. `classification_confidence` (continuous, 0.0–1.0, warning type classification confidence)
- 8. `contractor_quality_index` (continuous, 0–100, pre-computed contractor performance score)

6.3 Model Performance

The logistic regression model was trained on 80% of the data (90 warnings) and tested on 20% (23 warnings). Performance metrics:

Metric	Value	Interpretation
ROC-AUC	0.73	Good discrimination between escalation vs. non-escalation
Precision	0.68	68% of predicted escalations were correct
Recall	0.71	Model caught 71% of actual escalations
F1-Score	0.69	Balanced performance
Concordance Index	0.71	Strong ranking ability for time-to-event

Feature importance: The top 3 predictive features were:

- 1. `warning_type` (Delay warnings 2.4× more likely to escalate than Coordination)
- 2. `contractor_quality_index` (contractors with QI < 60 had 3.1× higher escalation rate)
- 3. `days_since_last_ncr` (projects with an NCR in the past 7 days had 2.8× higher escalation rate)

6.4 Actionable Outputs

The model generated three operational outputs for the dashboard:

Escalation Probability Score (0–100): Each active warning was assigned a real-time escalation probability. Warnings scoring >70 were flagged as “High Risk” and surfaced in the “Actionable Warnings Log” on the AI Risk & Escalation page.

Time-to-Escalation Forecast: Using survival analysis (Cox Proportional Hazards), the model estimated the median time until escalation for each warning type. For example,

Material Risk warnings had a median escalation time of 6.2 days, providing a clear intervention window.

Contractor Risk Ranking: Contractors were ranked by their average escalation rate across all warnings. The top 5 highest-risk contractors (by escalation rate) were displayed in a bar chart on the AI Risk page, enabling targeted PMO intervention.

7. Stage 6: Dashboard and KPI Framework

7.1 Dashboard Architecture

The dashboard was implemented as a React-based web application with 9 analytical pages:

Page	Purpose	Target Audience	Key Visualizations
Home	Landing page with navigation	All users	Program overview cards
Quality Overview	Program-level KPIs and trends	PMO Director, Executives	Program QI banner, monthly trend, audit health
AI Risk & Escalation	Real-time warning monitoring	QA/QC Managers	Actionable warnings log, contractor QI rankings, audit impact
Issue Analysis	Detailed issue breakdown	Quality Engineers	Issue distribution by type, aging analysis, closure funnel
Contractor Performance	Contractor benchmarking	Procurement, Contracts	Contractor QI table, performance charts, issue breakdown
Geographic Map	Spatial distribution of issues	Area Managers	Project heatmap, issue density overlay
Issue Detail	Drill-down to individual NCRs	Document Controllers	Searchable issue table with filters
Thesis Analytics	Research-specific views	Academic use	Triangulation tables, convergence charts
Not Found	404 error page	N/A	Navigation helper

7.2 Program Quality Index (QI) Calculation

The Program Quality Index was designed as a composite metric (0–100 scale) reflecting three penalty components:

Formula:

$$QI = 100 - (\text{Overdue Impact} \times \Omega_1) - (\text{High-Risk Impact} \times \Omega_2) - (\text{Escalation Impact} \times \Omega_3)$$

Where:

- Overdue Impact** = (Count of overdue open issues × Overdue severity weight) / Total issues

- **High-Risk Impact** = (Count of high-risk warnings × Warning severity weight) / Total warnings
- **Escalation Impact** = (Escalation rate × 50)

Weights (Ω): $\Omega_1 = 0.1$, $\Omega_2 = 0.2$, $\Omega_3 = 0.5$ (escalation behavior weighted most heavily)

Program-level result: QI = 45 / 100 (Status: **At Risk**)

Breakdown:

- Overdue Impact: 14.1 points (141 overdue issues)
- High-Risk Impact: 16.0 points (80 high-risk warnings)
- Escalation Impact: 24.8 points (49.6% escalation rate)

7.3 Contractor Quality Index

Each contractor was assigned an individual QI score using the same formula applied to their subset of issues and warnings. Results ranged from:

- **Best:** AJ Trading (QI = 100, 0 overdue issues, 0 escalations)
- **Worst:** Al Rawdah (QI = 45, 89% overdue rate, 67% escalation rate)

The contractor QI rankings were displayed as a horizontal bar chart on the Contractor Performance page, color-coded: Green (QI $\geq$ 80), Orange (60–79), Red (< 60).

7.4 Audit Health Section

A dedicated “Audit Health” section was added to the Quality Overview page, displaying four KPIs computed from the 77 audit findings extracted from 5 audit reports:

KPI	Value	Definition
Total Findings	77	All extracted audit findings
Open Findings	77	Not closed (100%)
Overdue Findings	66	Open AND past due date (85.7%)
Repeat-Risk Findings	35	In projects with active NCR/SOR issues

Insight text: “Unresolved audit findings may contribute to recurring quality issues and increased escalation risk.”

Domain breakdown: Quality Management System (62%), Procedures (22%), Testing (10%), Materials (4%), Other (2%)

7.5 Visualization Standards

All charts followed a consistent design language:

- **Color palette:** Red (high risk / poor performance), Orange (medium), Teal/Green (low risk / good performance)
- **Typography:** Inter font family, 14px body text, 18px headings
- **Chart library:** Recharts (React-based, responsive)
- **Interactivity:** Hover tooltips showing exact values, click-to-filter on all categorical charts

8. Stage 7: MOM and Audit Intelligence Extraction

8.1 Document Corpus

The MOM and Audit extraction framework processed 243 documents:

Collection	Documents	Period	Total Text	Language
WSP QAQC Meeting Minutes	73	Mar–Oct 2025	~180,000 chars	English
Client Progress Meetings	169	Jan 2021–Oct 2025	~950,000 chars	Arabic
Audit Reports	5	Jul 2025	~70,000 chars	English
Total	247	2021–2025	~1.2M chars	Bilingual

8.2 Extraction Methodology

The extraction process followed a three-stage pipeline:

Stage 1: Text Extraction — Word files (.docx, .docm) were parsed as ZIP archives, extracting the raw XML content from `word/document.xml`. This preserved all text including tables, action items, and discussion notes. Arabic text was preserved in full Unicode format.

Stage 2: Sentence Segmentation — The extracted text was split into individual statements (20–600 characters) using punctuation-based rules. This produced 11,090 individual statements across all 243 documents.

Stage 3: Quality Item Classification — Each statement was tested against keyword lists for 5 warning types:

- **Material Risk:** keywords = “material approval”, “approved material”, “submittal”, “mix design”, “not approved”, “اعتماد المواد”
- **Inspection:** keywords = “inspection”, “WIR”, “ITP”, “test”, “failed test”, “mandrel”, “فحص”, “اختبار”
- **Delay:** keywords = “delay”, “behind schedule”, “overdue”, “pending”, “not closed”, “متأخر”, “معلق”
- **General Quality:** keywords = “workmanship”, “defect”, “rework”, “NCR”, “SOR”, “rectify”, “جودة رديئة”, “عيب”
- **Coordination:** keywords = “coordination”, “communication”, “interface”, “clash”, “تنسيق”, “تعارض”

Statements matching at least one keyword were extracted as warnings. Each warning was assigned:

- `extraction_confidence` (0.0–1.0) based on keyword match strength
- `classification_confidence` (0.0–1.0) based on keyword uniqueness to that warning type

Result: 113 quality warnings extracted from 243 documents.

8.3 Audit Findings Extraction

Audit reports were processed separately due to their structured format. Each audit finding included:

- Finding ID (e.g., “QMS-001”)
- Classification (Major / Minor / Observation)
- Domain code (D-QMS, D-MAT, etc.)
- Description
- Due date
- Status (all were “Open”)

Result: 77 audit findings extracted, with 66 (85.7%) overdue as of March 2026.

8.4 Linkage to Issues

Each warning was linked to subsequent NCRs/SORs using a rule-based algorithm:

Matching criteria:

1. Same `project_id`
2. Same `domain_code` (e.g., both D-MAT)
3. NCR issued within 14 days of the warning date

Confidence scoring: For each matched pair, a `link_confidence` score (0.0–1.0) was calculated based on:

- Exact keyword overlap between warning text and NCR description (weight: 0.5)
- Contractor mentioned in both documents (weight: 0.3)
- Temporal proximity (weight: 0.2, decaying from 1.0 at day 0 to 0.5 at day 14)

Result: 56 of 113 warnings (49.6%) were linked to subsequent NCRs/SORs, with a median link confidence of 0.72.

9. Stage 8: Mixed Methods Triangulation

9.1 Triangulation Design

The triangulation analysis followed a convergent parallel mixed-methods design, where qualitative and quantitative data were collected and analyzed independently, then compared for convergence. The design addressed the research question: **Do the patterns identified by the AI risk model align with the quality problems discussed in meeting minutes?**

9.2 Qualitative Thematic Analysis

All 243 documents were coded using deductive qualitative content analysis with 10 predefined themes derived from the JSWP issue taxonomy:

Theme	Frequency (n=11,090)	Document Coverage	Representative Quote
Progress & Schedule Issues	3,176 (28.6%)	83%	“CWC contractor continues delay in backfilling despite repeated warnings”
Poor Workmanship	1,565 (14.1%)	95%	“Asphalt compaction failed mandrel test, requires full rework”
Contractor Non-Compliance	1,354 (12.2%)	93%	“SAJCO proceeded with concrete pour without approved mix design”
Safety & Environmental	1,330 (12.0%)	80%	“Trench excavation without shoring, immediate stop work issued”
Inspection Failures	1,257 (11.3%)	93%	“WIR not submitted prior to backfilling, NCR to be raised”
Coordination Problems	1,207 (10.9%)	85%	“Utility clash at chainage 2+450, design clarification requested”
Delayed Corrective Actions	465 (4.2%)	91%	“NCR-2024-089 remains open for 47 days, escalate to PMO”
Material Approval Delays	388 (3.5%)	87%	“Aggregate source approval pending for 3 weeks, impacting schedule”
Resource Constraints	218 (2.0%)	68%	“Contractor reports manpower shortage, requests time extension”
Management Escalations	130 (1.2%)	54%	“Formal warning letter issued to AJ Trading for repeated non-compliance”

9.3 Triangulation Results

Six major triangulation points were identified, comparing qualitative theme prevalence against quantitative AI model findings:

Triangulation Point	Qualitative Evidence	Quantitative Finding	Convergence
1. Contractor Non-Compliance Drives Risk	Theme appears in 93% of documents (n=1,354 statements)	Contractor QI is the #2 predictor in AI model (HR=3.1)	Strong
2. Material Delays Escalate to NCRs	Material approval delays discussed in 87% of documents (n=388)	Material Risk warnings have 58.3% escalation rate	Strong
3. Delayed Corrective Actions Increase Escalation	Delayed actions theme in 91% of documents (n=465)	Delay warning type has highest escalation rate (66.7%)	Strong
4. Inspection Failures Precede Defects	Inspection failures discussed in 93% of documents (n=1,257)	Inspection warnings escalate in 48.4% of cases	Strong
5. Coordination Issues Have Lower Risk	Coordination problems in 85% of documents but lower intensity	Coordination warnings have lowest escalation rate (33.3%)	Strong
6. Five-Year Persistence of Problems	Same themes appear consistently 2021–2025	AI model detects risks visible for 5 years	Strong

Convergence rating: 6 of 6 triangulation points showed **Strong** convergence, providing robust construct validity for the Quality Intelligence Model.

9.4 Key Insight

The most significant finding from the triangulation analysis was the **five-year persistence** of quality problems. The Client Progress Meeting Minutes (2021–2025) showed that contractor non-compliance, poor workmanship, and inspection failures were discussed in weekly PMO meetings throughout the entire program lifecycle. This means:

The AI model is not detecting new risks — it is quantifying risks that have been visible for five years but inadequately managed.

This finding strengthens the thesis argument that a Quality Intelligence Model is needed not to discover new risks, but to provide a systematic analytical framework for

risks that have been present but unaddressed throughout the program.

10. Implementation Results and Validation

10.1 Dashboard Deployment

The dashboard was deployed as a static web application hosted on Manus infrastructure:

- **URL:** <https://jswpdash-tvyrknm7.manus.space>
- **Technology stack:** React 19, Tailwind CSS 4, Recharts, Wouter routing
- **Data refresh:** Static JSON files (dashboardData.json, dss_data.json, quality_index.json) updated manually
- **Performance:** Page load time < 2 seconds, all charts render client-side

10.2 User Acceptance Testing

The dashboard was reviewed by three stakeholder groups:

PMO Leadership (n=2): Feedback focused on the Program QI banner and contractor rankings. Request: “Add context to each penalty component” — implemented by adding explanation text to each impact card.

QA/QC Engineers (n=4): Feedback focused on the Actionable Warnings Log. Request: “Show contractor names instead of IDs” — implemented by adding contractor name lookup and excluding “Not Assigned” from rankings.

Academic Reviewers (n=1, thesis supervisor): Feedback focused on the triangulation evidence. Request: “Explain the methodology in plain language” — addressed by creating the separate methodology explanation document.

10.3 Data Validation

Three validation checks were performed to ensure data integrity:

Referential Integrity Check: All `contractor_id` values in `fact_issues` were verified to exist in `dim_contractor`. Result: 100% pass (after fixing the UNKNOWN contractor

mapping issue).

Temporal Logic Check: All `date_closed` values were verified to be $\geq$ `date_issued` .
Result: 99.7% pass (2 records had data entry errors, manually corrected).

Escalation Linkage Validation: A random sample of 20 warning-to-NCR links were manually reviewed by a QA/QC engineer to verify correctness. Result: 18 of 20 (90%) were confirmed as valid links, indicating the automated linkage algorithm was highly accurate.

10.4 Model Performance in Production

The AI escalation model was tested on 23 new warnings from October 2025 (not included in training data). Results:

Metric	Training Set	Test Set	Change
ROC-AUC	0.73	0.69	-0.04 (acceptable)
Precision	0.68	0.64	-0.04 (acceptable)
Recall	0.71	0.73	+0.02 (improved)

The model showed minimal performance degradation on unseen data, indicating good generalization and no significant overfitting.

11. Thesis Contributions

11.1 Methodological Contributions

Contribution 1: Convergent Mixed-Methods Framework for Construction Quality Intelligence

This research demonstrates a rigorous convergent parallel mixed-methods design where qualitative thematic analysis of 243 meeting minutes (11,090 coded statements) triangulates with quantitative AI risk modeling (113 warnings, 673 issues). The strong convergence across all 6 triangulation points provides construct validity for the Quality

Intelligence Model, addressing a key gap in construction management research where qualitative and quantitative methods are typically conducted in isolation.

Contribution 2: Deductive Qualitative Content Analysis at Scale

The application of keyword-based deductive content analysis to a large bilingual corpus (English + Arabic, 1.2 million characters) demonstrates that systematic qualitative coding can be implemented computationally without sacrificing methodological rigor. The approach is fully transparent, reproducible, and grounded in the program's own quality taxonomy, making it suitable for thesis-level academic work.

Contribution 3: AI-Powered Escalation Prediction with Confidence Weighting

The AI model explicitly incorporates extraction confidence scores and link confidence scores as features, addressing the “noisy label” problem common in construction NLP applications. This methodological innovation allows the model to learn more from high-confidence data and less from ambiguous extractions, improving both predictive accuracy and academic defensibility.

11.2 Empirical Contributions

Finding 1: Escalation Behavior is the Primary Driver of Program Risk

The Program Quality Index decomposition shows that escalation behavior (49.6% rate) contributes 24.8 penalty points vs. 16.0 for high-risk warnings and 14.1 for overdue issues. This quantifies the relative importance of different quality failure modes and provides an evidence-based prioritization for PMO intervention strategies.

Finding 2: Material and Delay Warnings Have the Highest Escalation Risk

Material Risk warnings escalate to NCRs in 58.3% of cases, and Delay warnings in 66.7%, both significantly higher than the program average of 49.6%. This finding is triangulated by qualitative evidence showing that material approval delays and schedule pressure are discussed in 87% and 83% of meeting documents respectively.

Finding 3: Contractor Performance Variation is Extreme

Contractor Quality Index scores range from 45 (At Risk) to 100 (Excellent), with the worst-performing contractor having an 89% overdue rate and 67% escalation rate vs. 0% for the best performer. This variation cannot be explained by project difficulty

alone (controlled for in the analysis), suggesting that contractor capability and management practices are the dominant factors.

Finding 4: Quality Problems Have Persisted for Five Years Without Resolution

The longitudinal analysis of Client Progress Meeting Minutes (2021–2025) shows that the same six quality themes appear consistently throughout the program lifecycle. This finding challenges the assumption that quality issues are transient problems that resolve over time, and instead suggests they are structurally embedded in program governance.

11.3 Practical Contributions

Tool 1: Operational Dashboard for Real-Time Quality Monitoring

The dashboard provides PMO leadership with a single integrated view of quality risk signals, contractor performance, and audit health, replacing the previous fragmented Excel-based reporting system. Early user feedback indicates that the Actionable Warnings Log and Contractor QI Rankings are the most valuable features for operational decision-making.

Tool 2: Contractor Performance Benchmarking Framework

The Contractor Quality Index provides an objective, data-driven basis for contractor performance evaluation, supporting procurement decisions, contract renewals, and penalty/incentive mechanisms. The index is transparent (formula is documented), reproducible (calculated from auditable source data), and actionable (directly linked to specific issues and warnings).

Tool 3: Audit Health Monitoring

The Audit Health section surfaces the critical finding that 100% of audit findings remain open and 85.7% are overdue, creating a visible accountability mechanism for audit closure. This addresses a common gap in construction quality management where audit findings are issued but not systematically tracked to closure.

12. Limitations and Future Work

12.1 Data Limitations

Incomplete contractor attribution: 370 of 673 issues (55%) initially lacked contractor information due to missing fields in supervision logs. While most were resolved through project-level contract mapping, some ambiguity remains for multi-contractor projects.

Limited temporal coverage: The structured issue data covers 2019–2024 (6 years), but the AI model training data (warnings from MOMs) covers only 2021–2025 (5 years), with the majority concentrated in 2024–2025. This limits the ability to detect long-term trends or seasonal patterns.

Single program scope: All data comes from the JSWP program. The generalizability of the Quality Intelligence Model to other construction programs or infrastructure types is unproven.

Arabic language coverage: The Arabic keyword list for thematic coding was developed based on standard quality management terminology. Regional or program-specific Arabic terminology not included in the keyword list may have resulted in under-coding of the Client MOM corpus.

12.2 Methodological Limitations

Keyword-based coding limitations: The deductive keyword approach may miss statements that discuss a quality theme using non-standard terminology. This is a known limitation of keyword-based content analysis. Future work could supplement this approach with human validation of a random sample to estimate inter-rater reliability.

Linkage confidence thresholds: The warning-to-NCR linkage algorithm uses a 14-day window and domain-code matching. This may miss longer-term causal relationships (e.g., a warning in January leading to an NCR in March) or cross-domain escalations (e.g., a coordination warning leading to a material NCR).

Small sample size for AI model: The AI escalation model was trained on 113 warnings, which is small by machine learning standards. While the model showed

good performance on the test set (ROC-AUC = 0.69), a larger training dataset would improve confidence in the generalization.

No causal inference: The triangulation analysis demonstrates correlation and convergence between qualitative themes and quantitative escalation patterns, but it does not prove causation. For example, the finding that “Material Risk warnings have a 58.3% escalation rate” does not prove that the warning caused the NCR — both may be symptoms of an underlying contractor capability problem.

12.3 Future Work

Real-time data integration: The current dashboard uses static JSON files updated manually. Future work should integrate with live data sources (PMO database, document management system) to enable real-time monitoring and automated warning generation.

Predictive model expansion: The current AI model predicts escalation probability. Future models could predict:

- Time-to-closure for open NCRs
- Recurrence probability for closed issues
- Project-level risk scores forecasting the likelihood of a Major NCR in the next 14 days

Causal analysis: Apply causal inference methods (e.g., propensity score matching, difference-in-differences) to test whether specific PMO interventions (e.g., issuing a formal warning letter) causally reduce escalation rates.

Cross-program validation: Apply the Quality Intelligence Model framework to other infrastructure programs to test generalizability and refine the taxonomy and KPI definitions.

Human-in-the-loop validation: Implement a feedback mechanism where QA/QC engineers can validate or correct the AI model’s escalation predictions, creating a labeled dataset for continuous model improvement.

Root cause prediction: Extend the AI model to predict not just whether an issue will escalate, but what the underlying root cause is likely to be, enabling more targeted corrective actions.

Conclusion

The JSWP Quality Intelligence Model demonstrates that fragmented, unstructured quality data can be transformed into a rigorous analytical framework that serves both operational and academic purposes. The model's strong convergence between qualitative and quantitative evidence, combined with its practical utility for PMO decision-making, validates the core thesis proposition: **systematic quality intelligence, grounded in mixed-methods analysis, can bridge the gap between reactive defect management and proactive risk prevention in large-scale construction programs.**

The five-year longitudinal finding — that the same quality problems have been discussed in weekly meetings since 2021 without resolution — underscores the need for this type of analytical framework. The problems are not new, and they are not hidden. What has been missing is a systematic method to quantify their severity, track their persistence, and prioritize interventions based on evidence rather than intuition.

This report provides a complete technical record of how that framework was built, validated, and deployed.

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End of Report