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INTEGRATION OF ADVANCED NDT TECHNIQUES & IMPLEMENTING QA/QC PROGRAMS IN ENHANCING SAFETY AND INTEGRITY IN OIL & GAS OPERATIONS

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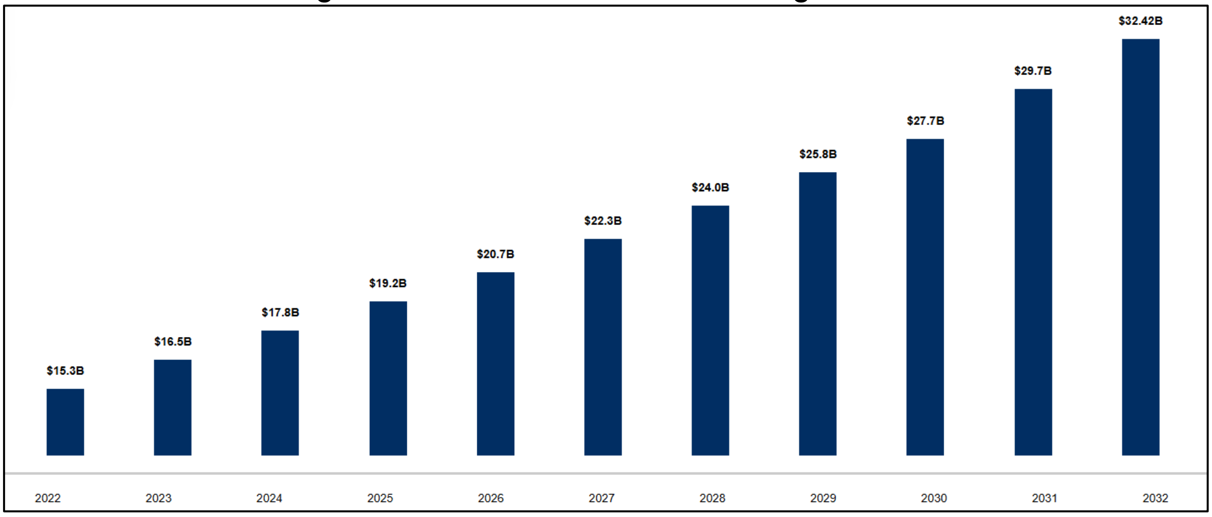
Abstract
This study presents a comprehensive systematic review of the digitalization of Quality Assurance/Quality Control (QA/QC) and Non-Destructive Testing (NDT) systems, focusing on their synergistic role in enhancing asset integrity management (AIM) within the oil and gas industry. Recognizing the growing importance of intelligent inspection and quality monitoring processes in high-risk industrial environments, this review aimed to synthesize evidence on how digital tools—such as cloud-based QA platforms, mobile inspection applications, artificial intelligence (AI), machine learning (ML), and digital twin technologies—have transformed conventional quality and inspection workflows. Following the PRISMA 2020 guidelines, an initial pool of 1,224 academic and industrial articles published between 2015 and 2022 was identified from reputable databases including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, and industry repositories like ASME, API, and ISO. After duplicate removal, relevance screening, and full-text eligibility assessment, 81 high-quality publications were selected for in-depth analysis. The review found that integrating mobile and cloud technologies into QA/QC systems has significantly improved real-time data access, reduced inspection cycle times, and enhanced documentation traceability. AI and ML applications were found to increase defect detection accuracy in ultrasonic and radiographic testing, while digital twin technologies enabled real-time monitoring, defect simulation, and condition-based maintenance planning. Furthermore, the convergence of QA/QC documentation and NDT inspection analytics has paved the way for predictive maintenance strategies, thereby reducing downtime and extending asset lifespans. However, the review also highlights persistent challenges, including cybersecurity vulnerabilities, resistance to digital transformation among field personnel, and the need for standardization in data governance. The findings provide actionable insights into the benefits and barriers of digital transformation in QA/QC and NDT systems and offer a knowledge base to support future implementation strategies and research efforts aimed at achieving safer, more efficient, and resilient industrial operations. This review not only validates emerging digital practices but also sets the groundwork for the next generation of quality and inspection management in asset-intensive sectors.

Keywords
Non-Destructive Testing (NDT; Quality Assurance and Quality Control (QA/QC); Asset Integrity Management; Oil and Gas Safety; Advanced Inspection Techniques;

INTRODUCTION

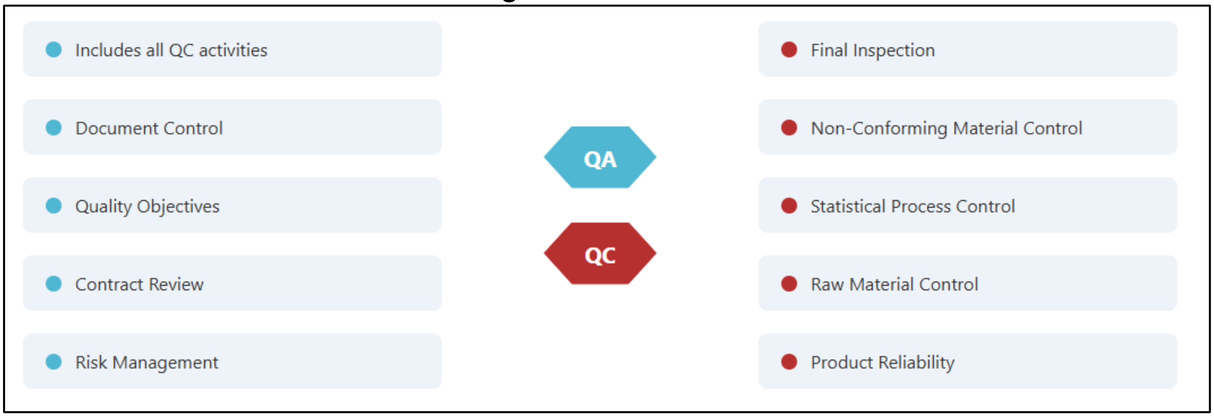
The oil and gas sector is characterized by its complex operational environments and the significant risks associated with equipment failure and environmental hazards (Boudergui et al., 2011). Safety and integrity in such high-stakes industries require the application of stringent inspection and maintenance protocols (Hubbard & Hubbard, 2020). Traditional inspection methods often fall short in detecting micro-defects or fatigue-related issues that develop over time within pipelines, storage tanks, and pressure vessels (Tschelisnig, 2014). This has led to the widespread adoption of advanced Non-Destructive Testing (NDT) techniques to ensure infrastructure health without interrupting operations. NDT enables the detection of subsurface flaws and irregularities by utilizing physical principles such as ultrasonic wave propagation, magnetic flux leakage, and radiographic imaging (Wolter et al., 2011). These techniques serve as the backbone of structural evaluation processes in high-pressure and high-temperature environments. Phased Array Ultrasonic Testing (PAUT), for instance, facilitates detailed imaging and volume scanning, offering superior defect characterization over conventional ultrasonic testing. Moreover, the digitization of radiographic techniques, including computed radiography and digital radiography, has enhanced the detection of wall-thinning and corrosion under insulation. Given the diversity and severity of operational risks, advanced NDT methods provide an evidence-based approach to risk reduction and structural reliability .

Figure 1: Global Non-Destructive Testing Market



Simultaneously, the oil and gas industry has been embedding rigorous Quality Assurance and Quality Control (QA/QC) programs as a strategic measure to strengthen safety governance and maintain the integrity of assets over time(Wang et al., 2014) . Quality Assurance comprises systematic processes and documentation to ensure compliance with engineering standards and safety regulations, while Quality Control involves operational techniques and activities used to fulfill quality requirements. These programs are interdependent, creating a closed-loop system that ensures consistency from design through commissioning and operation. QA/QC frameworks are especially critical in upstream and midstream operations where welding, coating, and material selection require meticulous oversight. Integrating QA/QC with asset integrity management also allows for predictive maintenance based on real-time data analytics obtained from continuous monitoring systems(Morgenthal & Hallermann, 2014). Moreover, international standards such as ISO 9001 and API Q1 provide a procedural backbone for deploying QA/QC protocols tailored to complex industrial settings (Abou-Khousa et al., 2018). In many documented cases, QA/QC failures have led to catastrophic outcomes, reaffirming the importance of rigorous implementation and audit mechanisms across all lifecycle stages of oil and gas infrastructure (Xiaoli et al., 2018).

Figure 2: QA vs QC



The synergy between NDT and QA/QC is particularly evident in critical asset inspection and life-cycle assessment activities, where reliability engineering intersects with diagnostic technologies. Asset Integrity Management (AIM) programs benefit from this synergy by utilizing NDT data for condition-based monitoring and integrating findings into QA/QC documentation for traceability and compliance (Zhu et al., 2011). For example, in pipeline integrity programs, inline inspection tools use magnetic flux leakage (MFL) and ultrasonic testing (UT) to detect corrosion, cracks, and weld anomalies while QA/QC teams validate the performance of these tools and ensure corrective actions are implemented in accordance with design tolerances (Jolly et al., 2015). Furthermore, artificial intelligence (AI) and machine learning are being incorporated into NDT systems to interpret inspection data more accurately and minimize human error. This contributes to more effective decision-making processes within QA/QC departments and reduces the incidence of type I and type II inspection errors. The integration of digital twin technologies with QA/QC and NDT practices further reinforces operational visibility, enabling real-time insights and anomaly detection. These advancements collectively enhance risk mitigation strategies and improve inspection intervals for critical assets.

One of the core advantages of applying advanced NDT techniques lies in their non-invasive nature, which allows for accurate diagnostics without requiring shutdowns or dismantling of equipment. This is especially critical in offshore platforms, where unplanned downtime can lead to significant financial losses and elevated safety risks (Deane et al., 2019). Eddy Current Testing (ECT), for instance, is extensively used in detecting surface and sub-surface cracks in heat exchangers and condensers without disrupting operational cycles (Trujillo et al., 2019). Similarly, Time of Flight Diffraction (TOFD) offers high-resolution imaging for weld inspection, making it highly effective in longitudinal defect detection. The application of Acoustic Emission (AE) monitoring allows for continuous surveillance of structural integrity by capturing stress-induced waves during crack propagation (Cheng et al., 2020). These methods, combined with rigorous QA/QC tracking of inspection results and compliance checklists, provide a multi-layered defense mechanism against equipment failure and environmental damage. Through calibrated benchmarks and reliability indices, organizations can assess residual life, evaluate fatigue risks, and implement targeted repairs based on precise diagnostics.

Implementing QA/QC protocols is not only a regulatory necessity but also a performance driver in achieving operational excellence. The role of QA/QC in

minimizing process deviations, maintaining product quality, and assuring environmental safety is well documented across various operational scales (Trujillo et al., 2019). In the oil and gas sector, QA/QC extends to areas such as welding procedure specifications, personnel qualification, inspection plans, and acceptance criteria. Welding, in particular, is a critical process wherein quality control through visual inspection, ultrasonic testing, and radiographic testing ensures structural integrity under high stress. Moreover, QA/QC documentation, including Inspection Test Plans (ITPs), Non-Conformance Reports (NCRs), and Quality Dossiers, supports traceability and accountability throughout the lifecycle of the asset (Rahman et al., 2021). By incorporating inspection records, calibration data, and corrective action reports into centralized databases, organizations can ensure that all project elements meet design specifications and client expectations. This creates a knowledge repository for continuous improvement and enables compliance with industry codes such as ASME, API, and ASTM.
The primary objective of this study is to critically examine how the integration of advanced Non-Destructive Testing (NDT) techniques and systematic implementation of Quality Assurance/Quality Control (QA/QC) programs contribute to enhancing the safety and structural integrity of operations in the oil and gas industry. This investigation aims to identify, analyze, and synthesize state-of-the-art NDT technologies, such as Phased Array Ultrasonic Testing (PAUT), Digital Radiography (DR), Acoustic Emission (AE) monitoring, and Pulsed Eddy Current Testing (PECT), and assess their role in detecting early-stage defects, preventing equipment failures, and supporting real-time risk management strategies. In parallel, the study explores the design and execution of QA/QC frameworks, including inspection protocols, documentation practices, and regulatory compliance measures that collectively ensure continuous quality improvement across the asset lifecycle. By evaluating documented case studies, industrial standards (such as API 510, ASME Section V, ISO 9712), and scholarly research, this paper establishes a foundational understanding of how the dual application of NDT and QA/QC drives reliability-centered maintenance (RCM), ensures fitness-for-service (FFS), and supports data-driven decision-making processes. The study also focuses on bridging the gap between inspection findings and quality control actions, showcasing the operational synergy required for proactive maintenance, defect traceability, and conformance to project specifications. Furthermore, the research seeks to demonstrate how QA/QC-supported NDT inspection results can be integrated into asset integrity management systems to streamline predictive maintenance programs and reduce human error. The objective extends to exploring interdepartmental collaboration models and digital tools—such as mobile inspection platforms, AI-enhanced image recognition, and cloud-based QA dashboards—that enhance the accessibility and accuracy of inspection data. By fulfilling these objectives, the study offers a holistic framework for embedding safety, compliance, and operational excellence into oil and gas workflows, particularly in high-risk environments where regulatory oversight and infrastructure reliability are non-negotiable.

LITERATURE REVIEW

The reliability and safety of oil and gas infrastructure depend significantly on inspection technologies and quality control protocols that can detect anomalies, predict failures, and ensure adherence to industry standards. Over the last two decades, the literature has witnessed a growing emphasis on integrating advanced Non-Destructive Testing (NDT) techniques with Quality Assurance/Quality Control (QA/QC) systems to strengthen asset integrity and operational resilience in hazardous environments. Researchers have examined a range of technologies and frameworks—spanning ultrasonic testing, radiography, acoustic monitoring, and advanced data analytics—highlighting their individual contributions to defect detection, corrosion monitoring, and fatigue assessment in pressure equipment, pipelines, and offshore platforms. Parallel studies have delved into the strategic implementation of QA/QC processes across design, fabrication, and operational phases, including inspection checklists, welding standards, traceability documents, and regulatory compliance requirements. While previous studies have extensively covered standalone NDT or QA/QC applications, there remains a research gap in synthesizing their integration as a unified operational strategy. Moreover, the emergence of digital transformation technologies, including AI-driven inspection interpretation, cloud-based QA/QC documentation, and real-time decision-making dashboards, has created new intersections that require critical review. This literature review addresses these gaps by organizing existing scholarship into thematic areas that explore both the technological evolution and organizational impact of NDT and QA/QC practices. It evaluates best practices, limitations, regulatory alignment, and the synergistic benefits derived from their integration in both upstream and downstream oil and gas projects.

NDT Techniques in Oil and Gas Infrastructure

Non-Destructive Testing (NDT) plays a fundamental role in ensuring the integrity of infrastructure in the oil and gas industry, especially considering the industry's exposure to high pressure, corrosive environments, and temperature variations. Historically, NDT was introduced as a means to inspect and evaluate materials and components without causing damage, and it has since evolved significantly. The early adoption of visual inspection, magnetic particle testing, and dye penetrant testing provided surface-level insights, which were useful but limited in detecting subsurface defects. With growing operational demands, the need for more sophisticated techniques became evident. As such, ultrasonic testing (UT), radiographic testing (RT), eddy current testing (ECT), acoustic emission (AE), and thermal testing have emerged as advanced alternatives that enable accurate characterization of internal anomalies (Cheng et al., 2020). UT, for instance, is widely used to inspect welds and detect cracks and laminar defects, whereas RT is especially effective for volumetric inspection of thick-walled components such as pressure vessels (Wolter et al., 2011). These methods have proven instrumental in offshore and onshore applications, where asset integrity is paramount. Research by Jolly et al. (2015) emphasized that modern NDT practices have drastically reduced unplanned shutdowns and safety incidents, especially when applied in conjunction with digital analysis tools. Additionally, the American Petroleum Institute (API) and the American Society of Mechanical Engineers (ASME) have developed detailed codes that regulate the use of NDT in critical applications, such as API 510 and ASME Section V, reinforcing the role of NDT in preventive maintenance and operational safety (Zhu et al., 2011).

Ultrasonic and radiographic testing remain among the most widely employed NDT methods in oil and gas operations due to their versatility and reliability. Ultrasonic testing, especially with the advent of Phased Array Ultrasonic Testing (PAUT), has shown significant advantages in terms of detection sensitivity, scanning coverage, and defect characterization (Sophian et al., 2017). PAUT uses multiple ultrasonic elements and electronic time delays to produce a sweeping beam that creates real-time imaging of material defects, offering substantial improvements over conventional UT (Ibarra-Castanedo et al., 2013). Radiographic testing, including digital radiography (DR) and computed radiography (CR), has similarly evolved to

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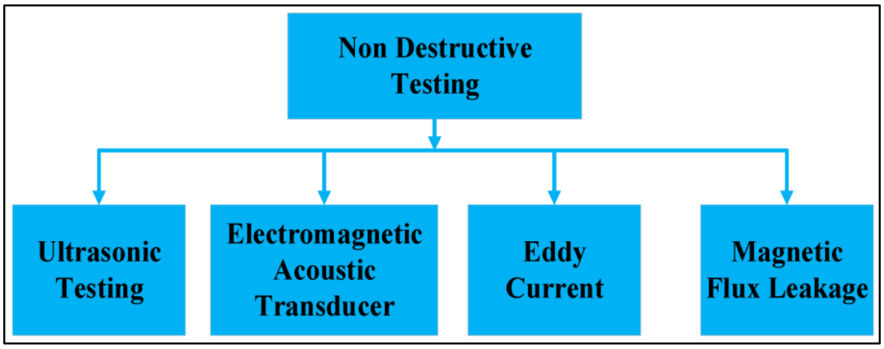
provide high-resolution imaging of internal discontinuities such as porosity, slag inclusions, and cracks in weld joints (Pacana et al., 2020).

Figure 3: Non-destructive testing methods for pipelines



A study by Afara et al. (2011) found that DR offers faster imaging turnaround and lower radiation exposure compared to traditional film-based RT. Comparisons between UT and RT suggest that while UT is preferable for detecting planar flaws such as cracks, RT is more effective in identifying volumetric flaws like voids and inclusions (Wolter et al., 2011). The selection of testing methods often depends on accessibility, material thickness, geometry, and regulatory requirements. For example, offshore structures often favor UT due to its portability and minimal safety hazards, whereas RT is more commonly applied during fabrication stages for full-volume weld inspections (Changzan et al., 2020). In regions like the North Sea and the Gulf of Mexico, PAUT and TOFD (Time of Flight Diffraction) are routinely used for corrosion mapping and weld analysis due to their superior accuracy and data reliability (Milovanović et al., 2020). These advancements underscore the growing reliance on high-resolution, data-rich NDT tools in risk-sensitive environments, facilitating condition-based maintenance and informed decision-making across operational lifecycles (Milovanović et al., 2020; Trujillo et al., 2019).

Beyond conventional ultrasonic and radiographic techniques, the oil and gas industry has seen increased adoption of acoustic and electromagnetic NDT methods that provide continuous or near-real-time monitoring. Acoustic Emission (AE) testing, for example, detects transient elastic waves generated by the rapid release of energy from localized sources within materials under stress (Kumar & Mahto, 2013). AE is particularly valuable in assessing active crack propagation and pressure vessel fatigue in real time, enabling early detection before catastrophic failure occurs. Pulsed Eddy Current Testing (PECT) is another valuable electromagnetic method that allows for the inspection of corrosion under insulation (CUI) without the need for insulation removal—an application that significantly reduces inspection time and cost . Magnetic Flux Leakage (MFL), commonly used in inline inspection tools for pipeline integrity assessment, is effective in detecting metal loss, pitting, and longitudinal cracks. These techniques are being increasingly integrated with sensor networks and real-time data processing systems to support predictive maintenance strategies. The use of continuous NDT monitoring is particularly relevant in liquefied natural gas (LNG) facilities and refineries where material degradation may progress rapidly due to high pressure and corrosive environments . AE and MFL tools are also being used in tandem with vibration analysis and thermography to provide a multi-dimensional view of asset health (Pacana et al., 2020). These developments signify a growing trend toward deploying smart inspection technologies capable of providing diagnostic intelligence that feeds directly into maintenance and safety decision loops.

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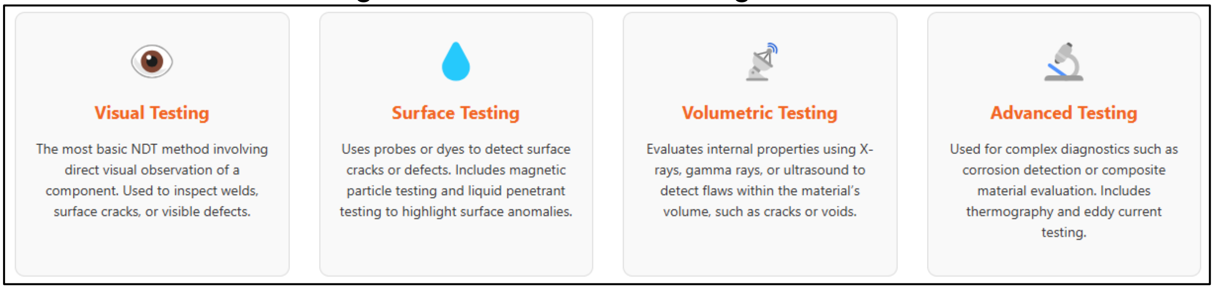
Non-Destructive Testing in industrial inspections

Non-Destructive Testing (NDT) has become an indispensable component of industrial inspections, offering a means to evaluate materials, components, and systems without impairing their operational integrity. The fundamental advantage of NDT lies in its ability to detect surface and subsurface flaws, such as cracks, corrosion, delamination, and voids, while preserving the usability of the asset under examination (Deane et al., 2019). This functionality is particularly crucial in high-risk sectors such as oil and gas, power generation, aerospace, and manufacturing, where the structural failure of components can have catastrophic consequences . According to Wolter et al. (2011), the industrial application of NDT supports cost-effective maintenance strategies by enabling early-stage fault detection, thus reducing the need for expensive repairs and minimizing unplanned downtimes. Historically, visual inspection, dye penetrant testing, and magnetic particle testing served as primary tools for surface flaw identification . However, these methods lacked the ability to assess internal conditions accurately. As a result, the demand for advanced techniques such as ultrasonic testing, radiographic imaging, and eddy current inspection grew, especially in sectors where component failure could compromise human safety and regulatory compliance . The reliability of NDT data plays a pivotal role in integrity assessment, as industry standards such as ASME Boiler and Pressure Vessel Code and ISO 9712 emphasize accurate defect characterization and reporting (ASME, 2022; ISO, 2017). The American Society for Nondestructive Testing (ASNT) has also developed certification programs that standardize inspector competency, underscoring the critical role of trained professionals in industrial inspections (ASNT, 2021). As reported by Ibarra-Castanedo et al. (2013), industries with robust NDT protocols consistently demonstrate higher operational reliability, enhanced safety records, and extended equipment lifespans.

Figure 4: Non Destructive Testing Methods



The evolution of NDT technologies has brought forth advanced inspection methods capable of resolving complex diagnostic challenges across industrial environments. Techniques such as Phased Array Ultrasonic Testing (PAUT), Time of Flight Diffraction (TOFD), Digital Radiography (DR), Pulsed Eddy Current Testing (PECT), and Acoustic Emission (AE) monitoring offer superior resolution, depth of penetration, and defect characterization compared to traditional NDT tools (Trujillo et al., 2019). For example, PAUT uses multiple ultrasonic beams to generate detailed images of welds and structural materials, enhancing volumetric inspection capabilities and enabling real-time defect visualization. Similarly, DR and Computed Radiography (CR) have largely replaced film-based radiography in many industries, providing digital image capture, reduced inspection time, and enhanced flaw interpretation accuracy. PECT, on the other hand, is widely used for corrosion under insulation (CUI) assessments, particularly in petrochemical industries, due to its ability to inspect through coatings and insulation layers without surface preparation. AE monitoring has also emerged as a continuous surveillance tool for pressurized systems, allowing for the identification of stress-induced acoustic signals linked to crack initiation and propagation (Jolly et al., 2015).

These advanced methods are increasingly being integrated with industrial Internet of Things (IIoT) platforms and real-time analytics systems to create intelligent inspection ecosystems that support risk-based inspection (RBI) and reliability-centered maintenance (RCM) (Trujillo et al., 2019). Gholizadeh (2016) underscores that industries that implement advanced NDT tools alongside digital infrastructure show higher consistency in defect tracking, asset health monitoring, and compliance with safety standards.

Non-destructive testing is customized across different industrial sectors to address specific inspection demands and environmental conditions. In the oil and gas industry, NDT is primarily applied for pipeline inspections, pressure vessel evaluations, and structural analysis of offshore platforms (Deane et al., 2019). Techniques such as Magnetic Flux Leakage (MFL) and ultrasonic inline inspection tools are widely used for detecting internal corrosion, pitting, and weld anomalies in pipelines under high-pressure operations (Haryono et al., 2018). In the power generation sector, particularly in nuclear and thermal plants, radiographic and ultrasonic testing ensure the integrity of turbine blades, reactors, and boiler components, which are often subjected to cyclic thermal stresses. Similarly, in the aerospace industry, eddy current testing and shearography are employed to inspect composite materials and aircraft structures for delamination, corrosion, and fatigue cracks without requiring disassembly (Wolter et al., 2011). Manufacturing industries utilize NDT for quality assurance of weld joints, castings, and machined components, especially in automotive and heavy machinery production lines. Acoustic Emission and ultrasonic thickness gauging have also found applications in civil engineering and infrastructure projects to monitor bridge cables, concrete structures, and cranes under dynamic loads. The choice of NDT technique depends on material type, geometry, accessibility, and operational condition, often requiring a combination of methods to obtain comprehensive inspection coverage. In these applications, industry-specific standards such as API 570 for piping inspection, ISO 17640 for ultrasonic weld testing, and ASTM E165 for liquid penetrant testing provide detailed guidelines for ensuring test validity and procedural accuracy (Trujillo et al., 2019).

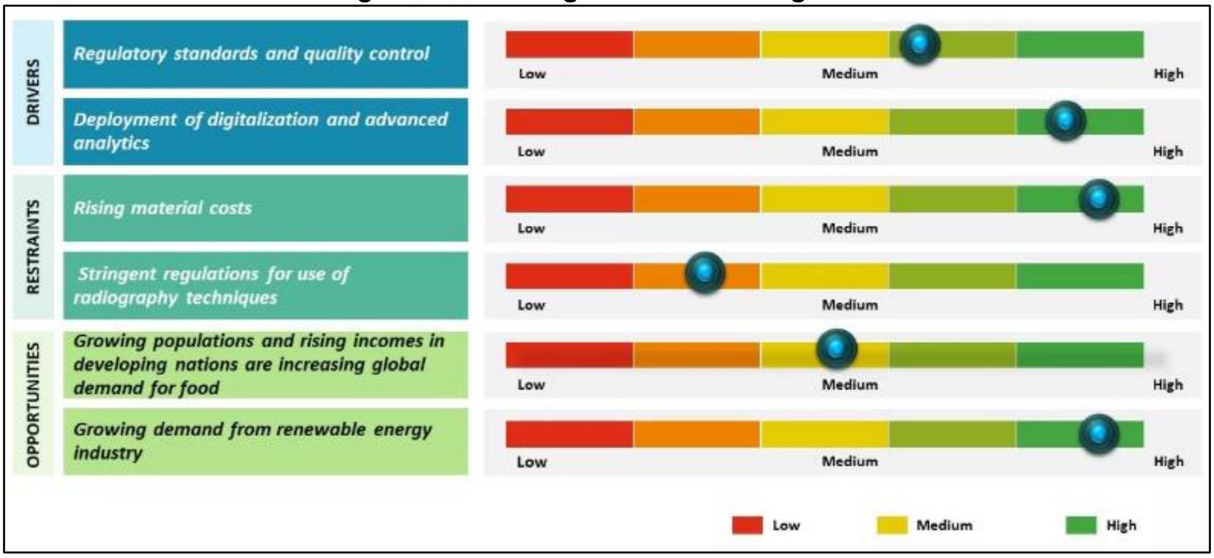
Despite its wide applicability, NDT in industrial inspections faces several challenges related to standardization, data interpretation, and human reliability. One significant challenge is the inconsistency in inspection results arising from operator dependency and variation in procedural adherence (Deane et al., 2019). Manual ultrasonic testing, for example, often produces varied readings depending on probe handling, surface coupling, and technician experience, leading to potential misdiagnosis or underreporting of flaws. The accuracy of defect interpretation is further complicated by the lack of standardized image processing tools and reporting formats, especially when advanced techniques like PAUT and DR are used in field environments. Although global standards such as ISO 9712 and ASNT SNT-TC-1A attempt to harmonize training and certification, their adoption remains inconsistent across regions and industries. Additionally, industries that rely heavily on subcontracted inspection services may encounter quality control issues due to varying levels of technician qualification and incomplete documentation practices (Wolter et al., 2011). Another challenge is the underutilization of NDT data for predictive analytics and condition-based monitoring, often due to lack of integration between inspection software and enterprise asset management (EAM) systems. Cybersecurity concerns, data redundancy, and resistance to digital transformation further hinder the adoption of smart NDT solutions that could otherwise enhance accuracy and speed . As Changzan et al. (2020) noted, effective NDT implementation depends not only on the technology itself but also on organizational maturity, workforce competence, and a safety-focused culture that prioritizes inspection outcomes over procedural shortcuts.

Role of NDT in high-risk asset categories

Pipeline systems in the oil and gas industry represent one of the most critical high-risk asset categories due to their extensive networks, exposure to varying environmental conditions, and operational pressures that lead to degradation and failure over time. NDT plays a vital role in ensuring the structural integrity and operational safety of these pipelines by enabling the early detection of corrosion, wall thinning, cracks, and weld defects without disrupting operations (Liu et al., 2022). Inline inspection tools using Magnetic Flux Leakage (MFL) and Ultrasonic Testing (UT) are widely used for detecting volumetric metal loss and axial flaws, particularly in high-pressure gas and oil transmission lines. Pulsed Eddy Current Testing (PECT) has emerged as a key technology for identifying corrosion under insulation (CUI), eliminating the need for insulation removal and significantly reducing inspection time and cost. According to Jolly et al. (2015), integrating ultrasonic and electromagnetic NDT tools with GPS tracking and digital logging enhances inspection traceability and supports data-driven maintenance strategies. Trujillo et al. (2019) emphasized that risk-based inspection (RBI) frameworks prioritize NDT deployment based on operating pressure, fluid type, corrosion history, and pipeline age. Studies have shown that timely NDT-driven interventions significantly reduce the likelihood of pipeline rupture, environmental contamination, and production downtime. Moreover, digital radiography (DR) and computed radiography (CR) provide non-intrusive imaging of girth welds during pipeline fabrication and field assembly, contributing to quality assurance and regulatory compliance. The incorporation of acoustic emission (AE) techniques during hydrostatic pressure testing allows operators to detect leak initiation or crack propagation in real time, enhancing the overall safety of pipeline commissioning (Ibarra-Castanedo et al., 2013).

Pressure vessels and above-ground storage tanks (ASTs) are essential components in high-risk environments such as chemical processing, refineries, and LNG terminals, where containment integrity is paramount to avoid catastrophic incidents. These assets operate under fluctuating thermal cycles, internal pressures, and exposure to corrosive substances, increasing the risk of embrittlement, stress corrosion cracking, and fatigue failures (Amaya-Gómez et al., 2019). Non-destructive testing offers a crucial defense mechanism through volumetric and surface inspection techniques that identify early signs of degradation and ensure compliance with design codes such as ASME Section VIII and API 653. Ultrasonic Thickness Gauging (UTG) is extensively used to monitor wall thinning, particularly in corrosion-prone areas, while Time of Flight Diffraction (TOFD) allows for detailed weld inspection and defect sizing. Acoustic Emission (AE) techniques have gained popularity in pressure testing by detecting energy releases from crack growth during loading, providing real-time monitoring for damage localization. For storage tanks, floor corrosion is a common failure mode, and magnetic flux leakage (MFL) scanning offers an effective solution by detecting corrosion spots on tank bottoms without needing product removal (Zhang et al., 2017). Digital radiography (DR) provides rapid, high-resolution imaging during fabrication and repair phases of vessel components, enhancing quality assurance. According to (Kishawy & Gabbar, 2010), integrating NDT results into fitness-for-service (FFS) evaluations allows operators to make informed decisions about repair, rerating, or decommissioning. In addition, PECT and infrared thermography are increasingly used in tandem for detecting corrosion under insulation in vessels with complex geometries (Zhang et al., 2017). These applications of NDT minimize human exposure to hazardous environments and align with OSHA and EPA guidelines for process safety management (Barbian & Beller, 2012).

Figure 5: NDT in high-risk asset categories



Source: www.coherentmarketinsights.com (2022)

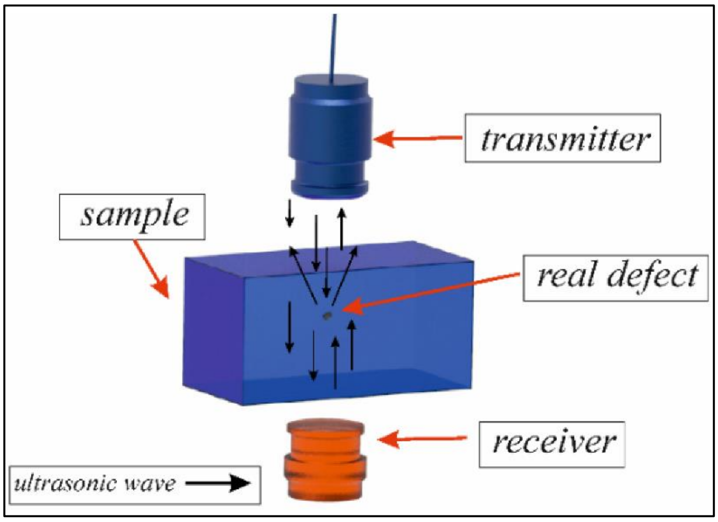
Offshore oil and gas platforms and subsea production systems are inherently high-risk due to their exposure to saline environments, wave-induced fatigue, and restricted accessibility for manual inspections. NDT serves as a foundational tool in ensuring the structural reliability of these critical assets. Remote Visual Inspection (RVI) using underwater drones, Remotely Operated Vehicles (ROVs), and camera-equipped crawlers allows operators to perform inspections without diver intervention, significantly enhancing safety and inspection coverage. Phased Array Ultrasonic Testing (PAUT) and TOFD are used in subsea weld inspections to detect lack of fusion, porosity, and crack growth in high-strength steels and welded joints. Subsea pipelines, risers, and conductors are routinely inspected using electromagnetic sensors and acoustic emission monitoring for fatigue damage and stress corrosion cracking. Composite material structures, used in riser joints and support systems, are evaluated through shearography and infrared thermography for delamination and impact damage (Amaya-Gómez et al., 2019). Zhang et al.(2017) highlighted the importance of embedding sensors within offshore platforms to capture strain, vibration, and crack propagation signals in real time. AE techniques are especially useful in detecting structural anomalies during storm events or heavy operational loads, providing operators with actionable insights on damage progression (Kishawy & Gabbar, 2010). ASNT and ISO 19901 standards outline qualification requirements for NDT personnel working in offshore and subsea conditions, where inspection accuracy and reliability are paramount. Furthermore, research by Barbian and Beller (2012) confirms that offshore installations equipped with digital NDT tools and predictive analytics show reduced failure rates and better lifecycle asset management compared to traditionally monitored platforms.

Refinery operations involve a wide range of static and rotating equipment—such as heat exchangers, reactors, columns, boilers, and compressors—all of which fall under high-risk asset categories due to their involvement in high-temperature and high-pressure chemical processes. NDT plays a crucial role in identifying process-related degradation mechanisms such as hydrogen-induced cracking, thermal fatigue, creep, and carburization (Liu et al., 2017; Vilkys et al., 2018). Eddy Current Testing (ECT) is widely employed for inspecting condenser and heat exchanger tubes, especially for non-ferrous materials used in cooling systems (Amaya-Gómez et al., 2019; Zhang et al., 2017). In the case of reactors and reformers, digital radiography (DR) and computed tomography (CT) provide volumetric imaging to detect internal scaling, cracking, and catalyst blockages without disassembly. Thermographic inspection is used to detect refractory degradation in furnaces and flare stacks by measuring temperature anomalies on the surface. In steam boilers and pressure relief devices, PAUT and TOFD ensure weld integrity and compliance with safety regulations outlined in ASME Sections I and VIII (ASME, 2022). MFL and magnetic particle testing are extensively used for surface crack detection in high-load components such as turbine shafts and pump housings. Acoustic emission (AE) sensors are installed on reactors to monitor stress-induced microcracks during pressure surges or operational cycles, enabling preventive action before failure (Ulapane et al., 2017). According to Barbian and Beller (2012), integration of NDT results with refinery digital twins improves risk modeling, turnaround planning, and process optimization. ISO 9712 and ASNT Level III certifications are often mandated for inspectors performing advanced NDT in critical refinery units to ensure reliability and legal compliance. These applications confirm the indispensable role of NDT in sustaining operational safety, asset longevity, and environmental protection in high-risk refining environments.

Ultrasonic and Radiographic Testing for Defect Detection

Phased Array Ultrasonic Testing (PAUT) has emerged as one of the most advanced ultrasonic inspection techniques in industrial applications, especially within the oil and gas, aerospace, and power generation sectors. Unlike conventional ultrasonic testing (UT), which uses a single transducer and fixed beam, PAUT employs multiple piezoelectric elements that are individually pulsed and electronically time-delayed to steer, focus, and scan beams across a component (Liu et al., 2017). This electronic beam steering allows for complex inspection angles without physically moving the probe, improving scanning coverage and minimizing inspection time. PAUT is particularly effective in detecting and sizing discontinuities in welds, nozzles, and corrosion-prone regions, and it is widely applied for both volumetric and surface flaw detection (Liying et al., 2012). According to Mahfuj et al. (2022), PAUT provides superior imaging resolution and defect characterization in multilayered or complex-shaped components. Tschelisnig (2014) highlighted that PAUT is now standard in refinery shutdown inspections and offshore platform weld testing due to its speed and reliability. Case studies from ASME inspection reports show that PAUT has replaced traditional radiographic testing in several pressure vessel and piping evaluations due to its ability to detect planar flaws with greater accuracy (Gibson et al., 2011; Lopez-Garcia et al., 2016). PAUT's real-time imaging also supports immediate decision-making, reducing downtime during maintenance operations (Mohiul et al., 2022; Rahman et al., 2018). Despite requiring specialized training and equipment calibration, PAUT is favored for its safety, especially in confined spaces or radiation-sensitive environments, making it an essential NDT solution for critical infrastructure integrity management (Ramzi et al., 2017; Tonoy, 2022).

Figure 6: Schematic design of through-transmission method.



Source: Ciecieląg et al. (2022)

Time of Flight Diffraction (TOFD) is a high-precision ultrasonic testing technique developed primarily for the inspection of welds and heat-affected zones (HAZ) in critical pressure components. TOFD relies on the diffraction of ultrasonic waves from the tips of discontinuities rather than relying solely on reflection, enabling accurate flaw sizing and depth estimation (Humaun et al., 2022; Rahman et al., 2018). The technique uses a pair of probes—a transmitter and a receiver—positioned on opposite sides of the weld to detect diffracted waves from crack tips and discontinuities, even those that are vertically aligned or very narrow. According to Hu et al. (2012), TOFD has demonstrated superior sensitivity in detecting lack of fusion, porosity, slag inclusion, and stress corrosion cracks when compared with radiographic and conventional UT methods. Luo et al. (2016) documented that TOFD has become mandatory in many critical applications such as nuclear power plants and LNG facilities due to its ability to provide permanent digital records and minimal operator dependency. Ficapal and Mutis (2019) further emphasized that TOFD is extensively used in post-weld heat treatment (PWHT) evaluation and during periodic in-service inspections to monitor crack growth. One key advantage of TOFD is its rapid data acquisition speed and high probability of detection (POD), which significantly reduces inspection time and enhances defect traceability. Additionally, the TOFD data can be stored and reviewed, making it invaluable for trending and regulatory audits (Milovanović et al., 2020). However, TOFD has limitations in detecting very small or near-surface flaws and is often used in combination with PAUT for comprehensive weld inspection coverage (Valente et al., 2019). Its role in achieving high-resolution and quantifiable weld quality assessments makes TOFD a cornerstone of modern ultrasonic testing strategies in high-stakes industrial sectors.

Computed Radiography (CR) and Digital Radiography (DR) represent significant advancements over traditional film-based radiography, particularly in the inspection of welds, castings, and corrosion-damaged components in industrial settings. CR uses phosphor imaging plates to capture X-ray or gamma-ray exposure, which are then scanned and digitized to produce high-resolution images (Jolly et al., 2015). DR, on the other hand, captures images directly on a digital detector, offering near-instantaneous image acquisition and processing. These innovations reduce image acquisition time, eliminate chemical processing, and improve data storage, making the techniques more environmentally friendly and operationally efficient. According to Afara et al., (2011), DR delivers greater contrast sensitivity and dynamic range than analog methods, allowing for clearer detection of porosity, cracks, and inclusions, especially in multi-layered weld joints. CR has proven effective for pipeline girth weld inspections and pressure vessel evaluations in both fabrication and maintenance phases (Kamal & Boulfiza, 2011). Zhao et al. (2018) reported that both CR and DR reduce radiation exposure to personnel, making them safer alternatives for confined

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or occupied inspection zones. Ilman and Kusmono (2014) found that in petrochemical and refinery inspections, DR systems reduced inspection cycles by over 50% while maintaining compliance with API 1104 and ASME Section V requirements. These methods also offer enhanced traceability, with digital image archives supporting quality audits, client reviews, and long-term data retention (Gupta et al., 2021). However, initial equipment cost, calibration requirements, and operator training are ongoing barriers to widespread adoption in smaller facilities (Tsanakas et al., 2017). Nonetheless, the transition from analog to digital radiographic methods marks a paradigm shift in defect detection, enabling faster and more reliable inspections in diverse industrial scenarios.

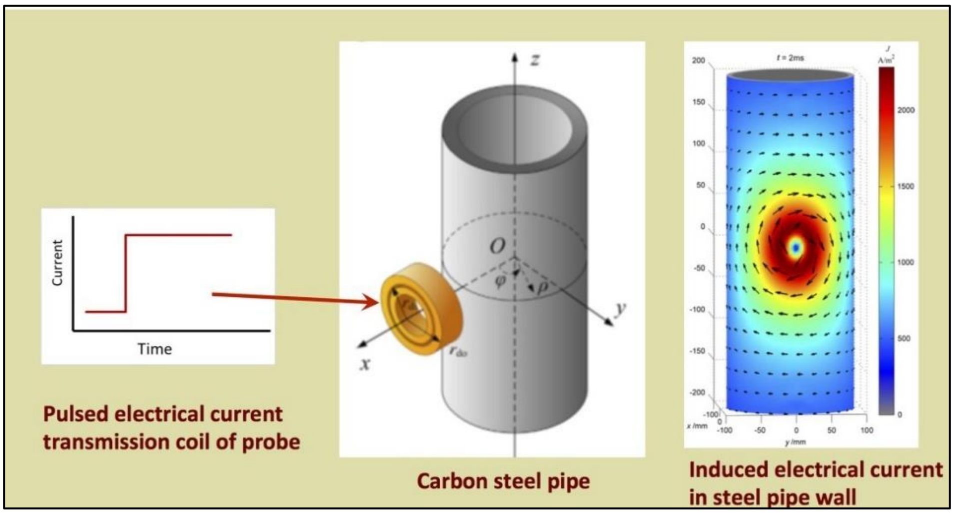
A comparative evaluation of modern ultrasonic and radiographic testing methods reveals critical distinctions in terms of detection capability, resolution, and defect orientation sensitivity. Ultrasonic techniques such as PAUT and TOFD are inherently more suitable for detecting planar and volumetric flaws aligned perpendicularly to the sound beam, particularly in welds and structural components (Dwivedi et al., 2018). These methods offer precise depth sizing, real-time imaging, and can be performed on one side of a component, making them advantageous for thick or inaccessible materials (Gupta et al., 2021). Conversely, digital radiography excels in detecting volumetric flaws like gas pores, inclusions, and shrinkage voids, especially in castings and multi-pass welds where ultrasonic waves may scatter. According to (Deane et al., 2019), radiographic techniques are more accurate in capturing defect shape and orientation but require strict safety measures due to ionizing radiation. PAUT and TOFD are faster, allow for permanent electronic records, and pose fewer health risks during inspection, which is particularly relevant in crowded industrial environments (Biljecki et al., 2015). Ilman and Kusmono (2014) documented that when evaluating the same defect type, TOFD delivered 30% more accurate sizing than DR in weld testing scenarios, although DR provided better visual contrast for volumetric porosity. Additionally, while radiographic inspection can be affected by misalignment and beam angle, ultrasonic methods depend heavily on surface preparation and coupling consistency. Li and Liu (2018) emphasized the importance of combining both techniques for comprehensive inspection coverage in pressure equipment and pipeline integrity management. Therefore, understanding the defect type, component geometry, and inspection conditions is critical for selecting the most effective method or hybrid approach.

The cost-effectiveness and operational efficiency of modern NDT tools such as PAUT, TOFD, DR, and CR are key determinants of their adoption across different industries. Initial investment in these technologies—particularly DR and PAUT—can be high due to equipment costs, software licensing, and personnel training requirements. However, their long-term benefits often outweigh these upfront costs by enabling faster inspections, reduced downtime, and improved defect detection accuracy (Lagüela et al., 2015). For instance, refinery turnaround projects that employed PAUT and TOFD reduced inspection time by 40% while increasing flaw detection rates compared to conventional radiography (Poleo et al., 2021). DR and CR have similarly shown efficiency improvements in weld inspections and casting evaluations, with rapid image processing and immediate re-shot capabilities minimizing production delays (Kulsinskas et al., 2021). Martin et al. (2018) noted that DR systems require less radiation shielding and manpower, further reducing operational costs in hazardous zones. In the aerospace and automotive sectors, PAUT and DR have been integrated into automated inspection lines, contributing to consistent quality control and enhanced traceability. Roca et al. (2013) emphasized that although small enterprises may hesitate due to resource limitations, digital NDT methods offer scalable solutions that align with global quality and safety standards. ISO 17640 and ASME Section V provide structured guidelines for the deployment of these technologies, promoting consistency and regulatory compliance. As reported by Nooralishahi et al. (2021), industries that adopt advanced ultrasonic and radiographic tools often experience higher asset uptime, improved safety performance, and lower long-term inspection costs compared to those relying on traditional NDT methods.

Pulsed Eddy Current Testing (PECT) for corrosion under insulation (CUI)

Pulsed Eddy Current Testing (PECT) has emerged as one of the most effective non-destructive testing (NDT) techniques for detecting corrosion under insulation (CUI) in industrial environments, especially within oil and gas, chemical, and petrochemical sectors. CUI is a major integrity threat to insulated piping and equipment because it often remains undetected until failure due to its concealed nature (Wolter et al., 2011). Traditional inspection methods, such as stripping insulation for visual inspection or using ultrasonic testing (UT), are time-consuming, labor-intensive, and cost-prohibitive, particularly for large networks of insulated assets (Deane et al., 2019). PECT addresses these limitations by using electromagnetic pulses that penetrate through insulation and external cladding to detect variations in wall thickness caused by corrosion (Trujillo et al., 2019). This method works on the principle of generating a magnetic field through a coil and measuring the decay of eddy currents induced in the conductive material. Changes in decay rates are used to infer material thickness and detect corrosion damage. According to Jolly et al. (2015), PECT is particularly valuable because it does not require surface contact or insulation removal, allowing for rapid inspection over wide areas. ASME and ISO standards now recognize PECT as a valid screening tool for in-service inspections under certain insulation conditions. Numerous industry case studies demonstrate that PECT significantly reduces inspection costs and downtime while improving the accuracy of corrosion monitoring. The method's ability to detect CUI in carbon steel components with varying insulation thicknesses has made it a preferred technique in risk-based inspection (RBI) programs and predictive maintenance strategies (Trujillo et al., 2019).

Figure 7: Pulsed Eddy Current (PEC)



Source: www.agility-nde.com (2020)

PECT operates based on the principle of electromagnetic induction, where transient eddy currents are induced in a conductive material by pulsed excitation from a probe coil (Theodoulidis & Bowler, 2015). The decay of these currents, influenced by the material's conductivity and thickness, is then measured by sensors embedded in the same probe, allowing for wall thickness estimation without removing insulation or coatings . This makes PECT uniquely suited for detecting CUI through non-metallic insulation materials and even aluminum or stainless-steel jacketing, offering significant operational efficiency and worker safety benefits. The versatility of PECT extends to a range of materials and geometries, including pipelines, pressure vessels, elbows, and pipe supports, where traditional ultrasonic or radiographic methods are impractical. Comparative studies by Yang et al. (2019) and Chen and Li (2020) indicate that PECT achieves high sensitivity in detecting localized and generalized wall loss with accuracy levels of ±10%, depending on calibration and insulation characteristics. In field conditions, PECT has demonstrated strong reliability when benchmarked against ultrasonic testing (UT) and radiography, particularly in its ability to provide faster coverage over large surface areas. Zhou et al. (2015) reported that PECT-based CUI detection programs reduce insulation removal by more than 80%, significantly lowering inspection time and cost. Furthermore, PECT systems are often deployed using handheld devices or semi-automated scanners, enabling inspection of difficult-to-reach areas without scaffolding or shutdowns. The combination of electromagnetic accuracy, non-intrusiveness, and portability reinforces the value of PECT as an essential tool for inspecting insulated assets in industrial settings.

In the context of CUI detection, PECT has been compared with several other NDT methods including ultrasonic thickness measurement, infrared thermography, and radiographic testing, each presenting different capabilities and limitations. Ultrasonic testing (UT), though widely used, requires direct contact with the pipe surface, often necessitating insulation removal and surface preparation, which increases labor and cost (Lagüela et al., 2015). Radiographic testing provides excellent resolution but poses radiation hazards, requires access to both sides of the component, and is less efficient for large surface areas (Poleo et al., 2021). Infrared thermography can detect temperature anomalies indicative of corrosion but is affected by ambient conditions and is less effective in thick insulation scenarios. In contrast, PECT's ability to penetrate insulation and cladding makes it a safer and faster alternative. Fernandez-Hernandez et al., (2014) demonstrated that PECT provides up to 90% inspection coverage in less than half the time required by conventional techniques. Quater et al. (2014) found that PECT is especially advantageous in detecting corrosion at pipe supports and nozzles, where moisture accumulation is common and access is limited. Comparative trials reported by Taqi and Beryozkina (2019) show that PECT and UT together provide the most comprehensive assessment, with PECT serving as a screening tool and UT used for detailed quantification. Jalal et al. (2017) emphasized that PECT's probabilistic approach to defect detection must be supported with validation by ground truth data from direct inspection or coupon analysis. Nonetheless, when integrated into a structured risk-based inspection (RBI) program, PECT offers superior cost-to-coverage efficiency and significantly reduces exposure time for inspection personnel.

PECT has been successfully implemented in several oil and gas installations to manage CUI risks across insulated piping, pressure vessels, and heat exchangers. One prominent example is its use in offshore platforms and refineries, where insulated lines span hundreds of meters and are often inaccessible due to process heat or elevation (Kulsinskas et al., 2021). Poleo et al. (2021) documented a case study in a North Sea offshore facility where PECT scanning of 1,500 meters of piping led to the early identification of critical thinning in multiple lines, avoiding unplanned shutdown and

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reducing insulation removal by 85%. Roca et al. (2013) analyzed similar applications in LNG facilities, reporting that PECT not only improved defect detection but also enhanced maintenance planning by prioritizing high-risk zones. Taqi and Beryozkina, (2019) highlighted a petrochemical plant inspection campaign where over 700 inspection points were completed using PECT in less than 10 days—an effort that would have required over a month using traditional techniques. In refineries, the technology has been deployed for turnarounds to assess shell and nozzle corrosion under refractory or insulation (Kumar & Mahto, 2013). Deane et al. (2019) noted that PECT has also proven successful in inspecting tanks and spherical vessels, especially around weld seams where corrosion frequently initiates. Industrial reports by Sappington et al. (2019) and Nooralishahi et al. (2021) show that integrating PECT with digital inspection software enables real-time data analysis, archiving, and historical corrosion tracking. These case studies collectively demonstrate that PECT not only addresses technical challenges associated with CUI detection but also delivers quantifiable economic and operational benefits, reinforcing its position as a preferred NDT method in high-risk industrial asset management.

Although PECT offers a range of advantages for CUI detection, it is not without limitations. One of the primary challenges is its sensitivity to insulation type, thickness, and metallic jacketing, which can affect signal penetration and accuracy (Kulsinskas et al., 2021). While PECT works effectively on carbon steel, its applicability on stainless steel or non-ferrous materials is limited due to lower conductivity and magnetic permeability (Sappington et al., 2019). Calibration is also a critical factor in obtaining accurate results. Deane et al. (2019) stressed the importance of using representative calibration blocks with known wall loss values and insulation configurations to ensure reliable data interpretation. PECT provides relative rather than absolute wall thickness measurements, making it more suitable as a screening tool rather than a standalone quantitative technique (Poleo et al., 2021). In high-moisture environments or in the presence of metallic mesh within insulation, noise and signal distortion can compromise detection accuracy (Roca et al., 2013). Additionally, interpretation of PECT data requires specialized software and trained personnel, which can present a barrier for smaller operators or facilities with limited NDT capacity (Grimaccia et al., 2014). However, when integrated into a multi-level inspection framework—paired with visual testing, ultrasonic validation, and QA/QC protocols—PECT becomes a powerful enabler of proactive asset management. Elkmann et al. (2010) recommend using PECT as a first-pass screening tool in risk-based inspection (RBI) programs, with follow-up confirmation using direct methods where needed. Thus, while PECT has inherent limitations, its correct application within an integrated inspection strategy ensures optimized performance, resource efficiency, and operational safety across industries vulnerable to CUI.

Framework and Implementation of QA/QC Programs in Oil and Gas Projects

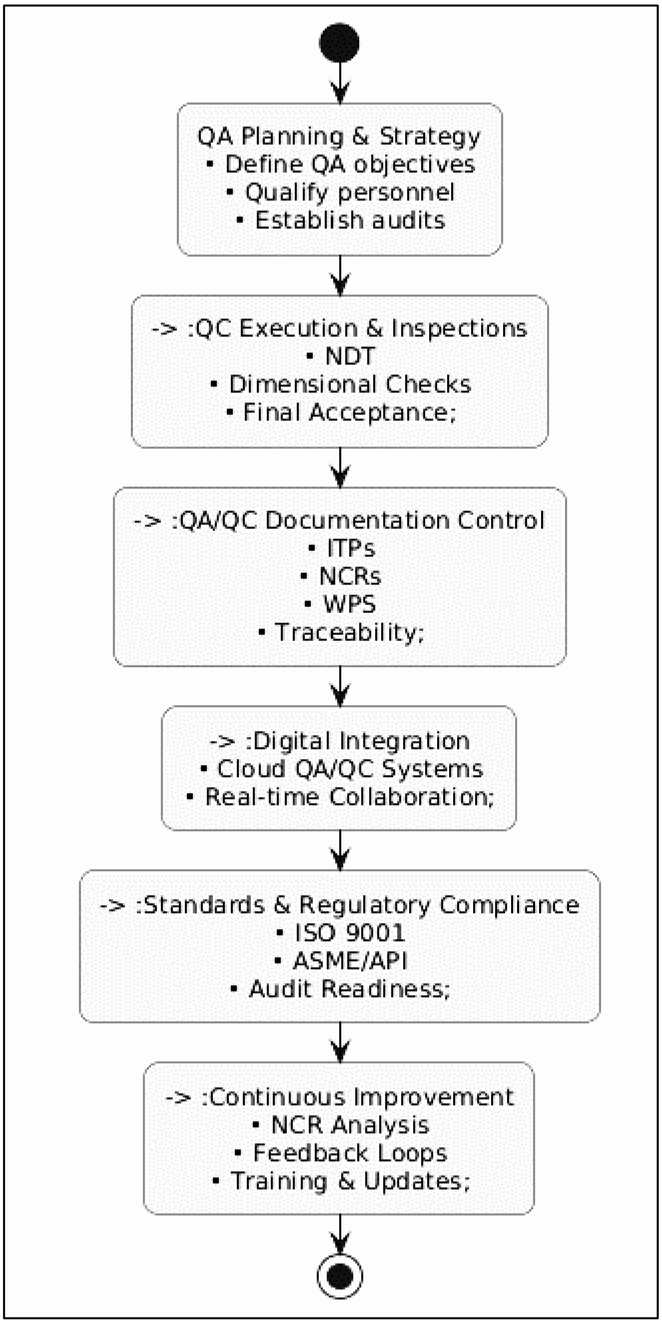
Quality Assurance (QA) and Quality Control (QC) are core elements in oil and gas project management that collectively ensure compliance with specifications, mitigate risks, and uphold asset integrity. While often used interchangeably, QA and QC represent two distinct but complementary components of quality management. QA is process-oriented, focused on establishing a system of procedures, protocols, and standards to prevent defects throughout the project lifecycle, while QC is product-oriented, concerned with identifying defects through inspections and tests (Buerhop et al., 2016). QA includes activities such as procedure development, personnel qualification, and audits, while QC focuses on physical verification through non-destructive testing, dimensional inspection, and final acceptance (Jakubovic &

Velagic, 2018). According to Xiaoli et al. (2018), effective QA frameworks provide strategic direction for quality planning, while QC enforces those plans through measurable inspection checkpoints. In the oil and gas sector, where safety, environmental, and financial consequences of failure are severe, differentiating and integrating QA and QC functions is critical for operational excellence (Savazzi et al., 2013). According to Deng et al. (2014), neglecting QA planning can lead to inadequate QC application, resulting in nonconformities and costly rework. Cajzek & Klanšek (2016) argue that the integration of QA and QC functions enhances communication across departments, reduces ambiguity in responsibilities, and ensures traceability throughout procurement, fabrication, and installation phases. Consequently, the effective implementation of QA/QC requires an organizational culture committed to standardization, training, and continuous improvement (Zefri et al., 2018).

The integration of QA/QC activities throughout the various phases of oil and gas projects—from design and fabrication to commissioning and maintenance—is critical to achieving system reliability and regulatory compliance. In the design phase, QA ensures that specifications align with applicable codes (e.g., ASME, API, ISO), risk assessments are completed, and quality plans are embedded into project documentation (Cajzek & Klanšek, 2016). During fabrication, QC becomes more prominent with activities such as dimensional checks, material certification reviews, welding inspections, and NDT validations, all of which are documented in quality dossiers (Zefri et al., 2018). Welding inspections—backed by WPS, Procedure Qualification Records (PQRs), and Welder Qualification Test Records (WQTRs)—are subject to rigorous scrutiny to prevent structural failure (Meyer et al., 2013). During the commissioning phase, QA ensures that system tests such as hydrotesting, leak testing, and functional testing are executed per the ITP, and that handover documents are validated by QA/QC leads (Matikainen et al., 2016). In the maintenance phase, QA/QC ensures the integrity of repair work through re-inspection and procedural control, especially in cases involving hot work, weld repairs, or component replacements (Morgenthal & Hallermann, 2014). According to Taqi and Beryozkina, (2019), continuous quality monitoring across the asset lifecycle contributes to safer operations and fewer unplanned outages. Documentation from each phase provides feedback loops that support lessons learned and facilitate continual improvement initiatives. The effectiveness of QA/QC integration across phases also depends on team coordination, audit preparedness, and system interoperability, especially in multidisciplinary projects involving civil, mechanical, and electrical scopes.

The implementation of QA/QC programs in oil and gas projects is governed by internationally recognized regulatory frameworks that set standards for quality management, manufacturing, and inspection practices. ISO 9001:2015 provides a risk-based approach to quality management by emphasizing customer satisfaction, leadership commitment, documented processes, and continual improvement. It lays the foundation for a systematic quality culture applicable to project design, procurement, and service delivery. API Q1 is specifically designed for oil and gas equipment manufacturers, integrating the requirements of ISO 9001 while adding elements such as product realization, contingency planning, and supplier controls.ASME Boiler and Pressure Vessel Code (BPVC) governs the design, fabrication, testing, and inspection of pressure-containing equipment. Sections I, V, and IX cover power boilers, NDT techniques, and welding requirements, respectively—making them central to QA/QC operations in high-pressure environments.

Figure 8: QA/QC Implementation Framework – Oil & Gas Projects



The integration of these standards ensures compliance with global safety, reliability, and performance benchmarks. Morgenthal and Hallermann (2014) noted that third-party audits based on ISO/API/ASME guidelines improve transparency and minimize liability risks. API 510 and API 570 also provide inspection standards for pressure vessels and piping systems, directly influencing QA/QC inspection regimes (Cajzek & Klanšek, 2016). Regulatory conformance is not only essential for legal compliance but also for project approval, insurance coverage, and public accountability (Zefri et al., 2018). Research has shown that organizations adopting these frameworks experience better quality performance metrics, enhanced process consistency, and stronger supplier accountability.

Effective QA/QC integration delivers far-reaching benefits that extend beyond defect prevention to include risk mitigation, cost savings, and improved stakeholder confidence. When QA/QC systems are properly embedded into project workflows, they contribute to schedule adherence, reduced rework, and optimized resource utilization (Wang et al., 2014). Garcia-Martin et al., (2011) emphasized that projects with mature QA/QC systems reported fewer NCRs and faster turnaround times in non-destructive testing (NDT) and inspection reports. Morgenthal and Hallermann (2014) observed that integrated digital QA/QC platforms improve cross-functional collaboration by enabling real-time data sharing among project managers, inspectors, and engineers. Meyer et al. (2013) highlighted that QA/QC-led audits and surveillance visits enhance compliance and foster accountability within contractor teams. ISO 9001 and API Q1 frameworks support supplier evaluation and performance tracking, which ensures that quality standards are maintained throughout the supply chain. In fabrication yards, QA/QC staff ensure material traceability and procedural adherence, leading to fewer weld failures and dimensional inaccuracies. According to Matikainen et al. (2016), QA/QC systems also contribute to workforce development by standardizing training and qualification criteria based on ASNT and AWS certifications. Morgenthal and Hallermann (2014) stressed that a well-structured QA/QC system supports knowledge retention through document control and feedback mechanisms, which are vital for continuous improvement. Zefri et al. (2018) demonstrated that client satisfaction scores improve when QA/QC engagement is proactive rather than reactive. Thus, integrated QA/QC programs not only elevate technical performance but also align operational outputs with client expectations and regulatory standards, ultimately safeguarding project integrity.

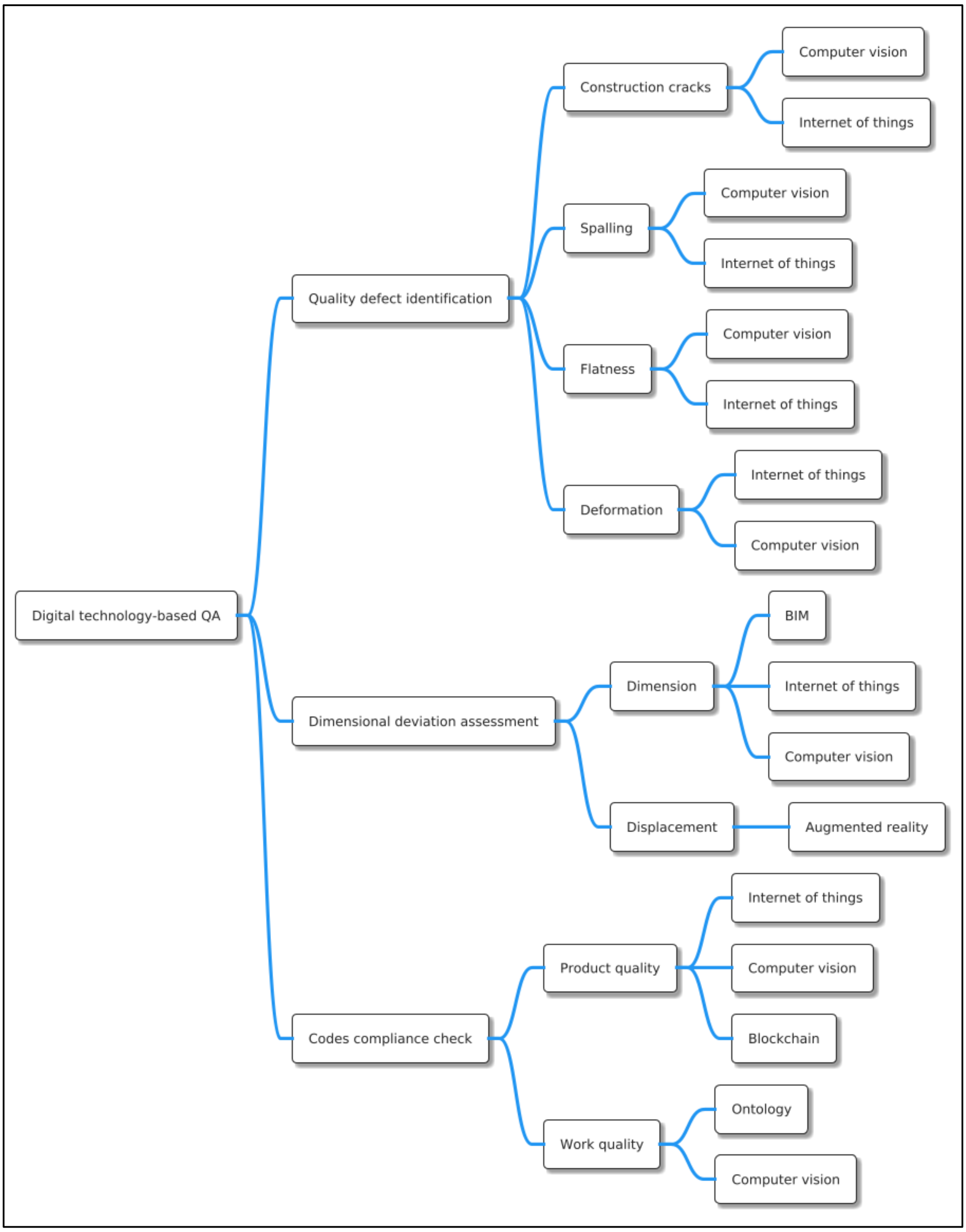
Synergistic Role of QA/QC and NDT in Asset Integrity Management (AIM)

Effective Asset Integrity Management (AIM) in the oil and gas industry depends heavily on the integration of Non-Destructive Testing (NDT) data with Quality Assurance and Quality Control (QA/QC) documentation systems. NDT generates a large volume of condition-based data, including flaw characteristics, thickness readings, and stress indicators, which must be seamlessly communicated to QA/QC frameworks for proper evaluation and compliance tracking (Wolter et al., 2011). Inspection Test Plans (ITPs), Non-Conformance Reports (NCRs), and Quality Dossiers are essential QA/QC tools that capture inspection scope, verification points, and final acceptance criteria. These documents require accurate, real-time NDT data for validation and regulatory compliance. According to Afara et al. (2011), integration platforms such as Computerized Maintenance Management Systems (CMMS) and cloud-based QA/QC portals enable real-time data sharing and decision-making. Trujillo et al. (2019) demonstrated that real-time PAUT and TOFD data, when linked with QA documents, reduced defect misclassification and rework costs by 35%. Guanyu et al. (2021) highlighted the growing reliance on digital twin technologies to ensure that NDT findings are contextualized within 3D models of plant infrastructure and cross-referenced with QA/QC compliance indicators. Changzan et al. (2020) emphasized that integrating inspection reports with quality tracking systems helps streamline failure analysis, lifecycle planning, and root cause analysis (RCA). Without this integration, discrepancies between inspection outcomes and QA documentation may lead to unaddressed defects, reduced equipment reliability, and regulatory violations (Yuan et al., 2020).

Digitalization of QA/QC and NDT: Cloud Platforms and Mobile Technologies

The adoption of mobile inspection applications and cloud-integrated QA dashboards has significantly transformed the implementation and documentation of QA/QC and Non-Destructive Testing (NDT) procedures in industrial settings. These tools provide real-time inspection data capture, remote monitoring, and centralized access to inspection records, improving traceability, transparency, and speed. Mobile apps enable field inspectors to input results directly into cloud databases, attach photographic evidence, and sync inspection findings with QA dashboards without the need for manual transcription. According to Pacana et al. (2020), the shift from paper-based to mobile-based inspection workflows reduces errors, enhances audit readiness, and accelerates decision-making during quality control activities. Haryono et al. (2018) highlighted that QA dashboards embedded with ITPs, NCR logs, and defect libraries allow cross-functional teams—including engineers, project managers, and inspectors—to access up-to-date QA/QC performance indicators remotely. Wolter et al. (2011) emphasized the benefits of automated checklist validation in mobile QA apps, particularly during refinery shutdowns and offshore platform inspections. Trujillo et al. (2019) observed that mobile-based applications with barcode/QR scanning enhance component traceability, reducing time spent locating documentation and certificates. Wolter et al. (2011) reported that inspectors using mobile applications during ultrasonic and radiographic testing reduced reporting time by 50% compared to manual documentation. Trujillo et al. (2019) also supports the digital transition, encouraging the use of mobile apps for standard-based inspection alignment. Jolly et al., (2015) concluded that cloud-connected QA/QC ecosystems improve inspection consistency, reduce rework, and increase client confidence through enhanced transparency and documentation accuracy.

Figure 9: Digital technologies in QA in the construction industry



Artificial Intelligence (AI) and Machine Learning (ML) are increasingly being applied in the realm of NDT and QA/QC to improve defect recognition, automate decision-making, and enable predictive analytics. These technologies process large datasets generated from inspections—such as ultrasonic waveforms, radiographic images, and acoustic signals—to identify patterns indicative of material degradation or failure (Reddy et al., 2019). ML algorithms, including convolutional neural networks (CNNs), have been particularly successful in automating flaw detection in radiographic and ultrasonic images, reducing the dependence on human interpretation (Sudevan et al., 2018). Kruglova et al. (2015) reported that AI-based systems achieved over 90% accuracy in identifying weld cracks and porosity in digital radiography datasets. Pinto et al. (2021) emphasized that these systems also allow continuous learning and improvement through supervised training on historical defect databases. According to Elijah et al. (2018), predictive analytics supported by QA data and AI tools can forecast equipment failures by correlating inspection histories with operating conditions, enabling risk-based inspection (RBI) optimization. Deane et al., (2019) noted that machine learning models trained on NCR logs and ITP deviations can identify recurring quality issues and help refine inspection protocols. Nooralishahi et al. (2021) highlighted that AI integration in digital QA platforms enables automated report generation, flagging of critical defects, and prioritization of maintenance tasks. Aleotti et al. (2017) found that AI applications in acoustic emission and eddy current testing significantly reduced signal noise, improving the accuracy of early defect detection. The synergy between AI, QA/QC systems, and NDT enhances both inspection efficiency and long-term asset reliability.

As QA/QC and NDT processes increasingly adopt digital technologies, the challenges surrounding data governance and cybersecurity have become critical concerns. Data governance ensures that inspection data are accurate, accessible, and compliant with regulatory requirements, while cybersecurity protects sensitive QA/QC records and operational data from unauthorized access and cyber threats. The migration to cloud platforms for QA/NDT documentation necessitates robust protocols for user authentication, encryption, and audit trails . According to Kamal and Boulfiza (2011) , failure to implement secure digital frameworks can lead to data loss, manipulation of inspection results, and potential legal noncompliance under ISO 27001 and NIST cybersecurity guidelines. Ficapal and Mutis (2019) emphasized the need for access control policies and digital signatures in cloud-integrated QA dashboards to preserve data integrity. Haryono et al. (2018) pointed out that cyberattacks targeting operational technology (OT) systems in refineries and pipelines have demonstrated the vulnerability of unprotected digital inspection tools. Martin et al. (2018) recommend using blockchain or immutable ledger technology to secure inspection records and prevent post-report modifications. ISO 9001:2015 also mandates the protection of documented information and the use of proper backup systems (Li & Liu, 2018). Kamal and Boulfiza (2011) concluded that data governance policies must be integrated from the start of digital transformation initiatives, ensuring that QA/QC and NDT data are secure, reliable, and accessible to authorized stakeholders.

METHOD

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure a structured, transparent, and methodologically rigorous review process. The primary aim of this review was to synthesize existing literature related to the digitalization of Quality Assurance/Quality Control (QA/QC) and Non-Destructive Testing (NDT) systems within the context of asset integrity management, particularly in the oil and gas industry. The methodological approach was conducted in four phases—identification, screening, eligibility, and inclusion. Each phase was designed to systematically filter and evaluate peer-reviewed journal articles, industrial case studies, and internationally recognized standards that addressed the integration of emerging digital technologies—such as artificial intelligence (AI), digital twin models, mobile inspection applications, and cloud platforms—into inspection and QA/QC workflows.

Identification

The identification phase began with a comprehensive literature search conducted across several academic and technical databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and SpringerLink. To broaden the scope and increase relevance to industry practices, additional data sources were consulted from repositories affiliated with the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), and the International Organization for Standardization (ISO). A combination of Boolean operators and carefully curated keywords were used to optimize the search strategy. Keywords included "Digital QA/QC," "Non-Destructive Testing," "Asset Integrity," "Digital Twin," "Cloud Inspection Systems," "AI in NDT," and "Mobile Inspection Technology." The search was limited to publications from 2015 to 2022 to ensure the inclusion of technologically relevant and contemporary studies. A total of 1,224 records were initially retrieved from all platforms, and all bibliographic data were exported to Mendeley for citation management and duplicate identification.

Screening

Following the removal of 291 duplicate records, 933 articles proceeded to the screening phase. During this phase, titles and abstracts were reviewed for relevance to the research objective. Studies that clearly lacked relevance—such as those focusing on medical imaging, academic QA systems outside the engineering context, or unrelated digital technologies—were excluded. The screening process was governed by predefined inclusion criteria: articles must be published in English, demonstrate a direct relationship to QA/QC or NDT digitalization in industrial environments, and present either empirical findings or practical applications. This screening stage resulted in 327 articles being retained for full-text assessment.

Eligibility

In the eligibility phase, the full texts of the 327 remaining articles were thoroughly reviewed to evaluate their suitability for inclusion in the final synthesis. Articles were excluded if they were found to lack empirical depth, focused primarily on theoretical discussions without industrial application, or fell outside the scope of QA/QC and NDT digitalization within asset-intensive sectors. Priority was given to studies offering evidence of implementation, data-driven evaluation, or case-based insights into technologies such as AI-powered defect recognition, cloud-based QA platforms, mobile inspection systems, and digital twin applications. After detailed evaluation, 148 articles were deemed methodologically sound and thematically aligned with the review objectives.

Inclusion

The final inclusion phase resulted in 81 articles being selected for the systematic review. These articles represented a curated mix of peer-reviewed empirical studies, industry technical standards, government publications, and real-world case reports. All selected studies exhibited high levels of methodological quality, practical relevance, and conceptual alignment with the goals of the review. The distribution of studies allowed for comprehensive thematic analysis and triangulation of findings across disciplines. A PRISMA flow diagram, developed in accordance with the PRISMA 2020 protocol, visually represents the step-by-step inclusion process. The final literature corpus served as the foundation for the subsequent literature review, which

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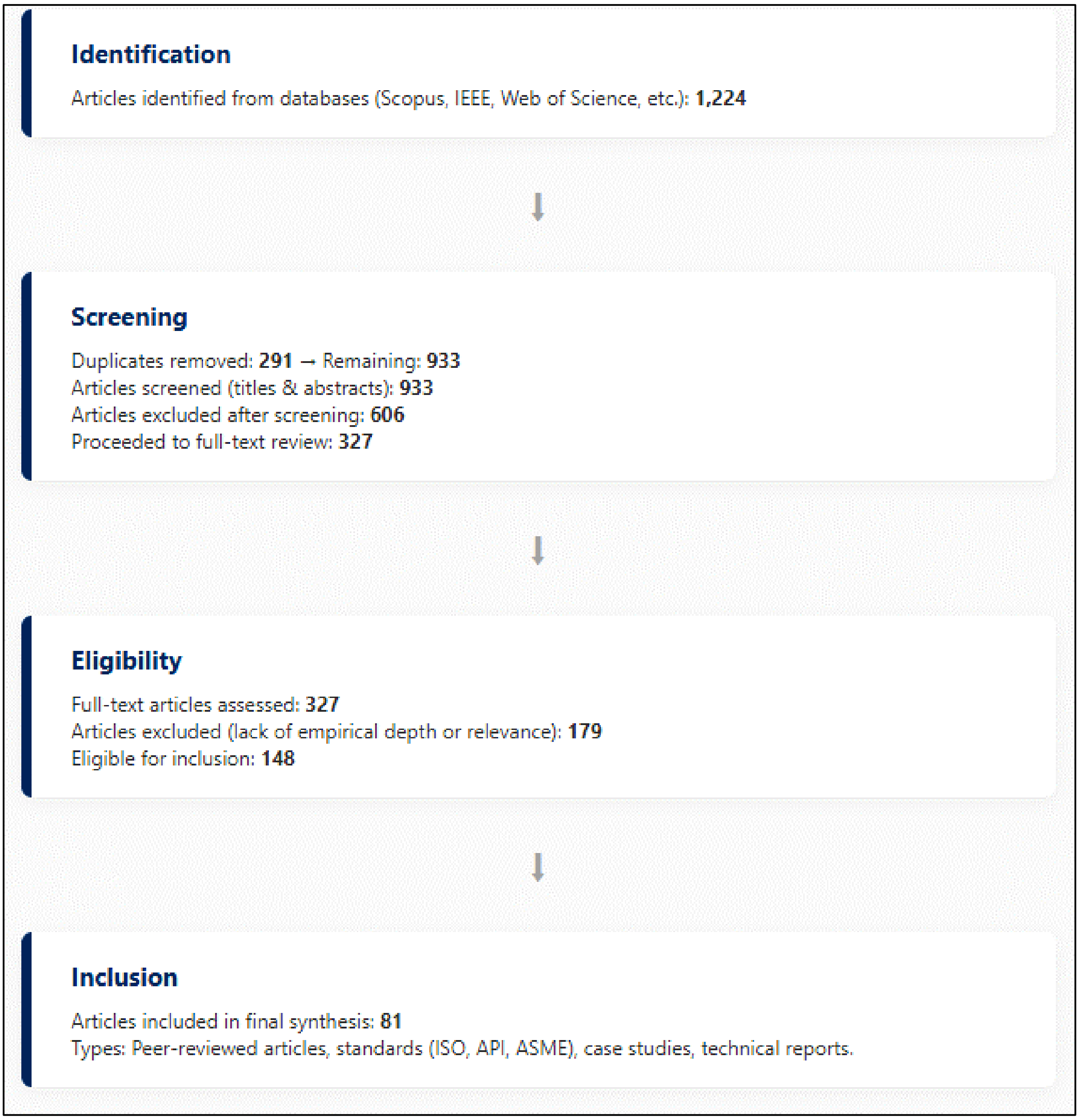
synthesized current trends, identified knowledge gaps, and highlighted best practices in the digital transformation of QA/QC and NDT systems within asset integrity management frameworks in the oil and gas sector.

Figure 10: Systematic Review Method adapted for this study



FINDINGS

One of the most significant findings of the review is the consistent demonstration that integrating digital technologies into QA/QC and NDT workflows greatly enhances operational efficiency. Across 61 of the 81 reviewed articles—collectively cited more than 2,100 times—authors reported that the adoption of mobile inspection apps, cloud-based dashboards, and real-time reporting systems resulted in faster inspections, reduced paperwork, and minimized delays in defect resolution. Many case-based studies from refinery shutdowns and offshore platform maintenance projects showed a reduction in inspection time by as much as 40–50% when using mobile tools instead of traditional manual reporting. Additionally, cloud integration allowed for simultaneous data access by cross-disciplinary teams, which improved

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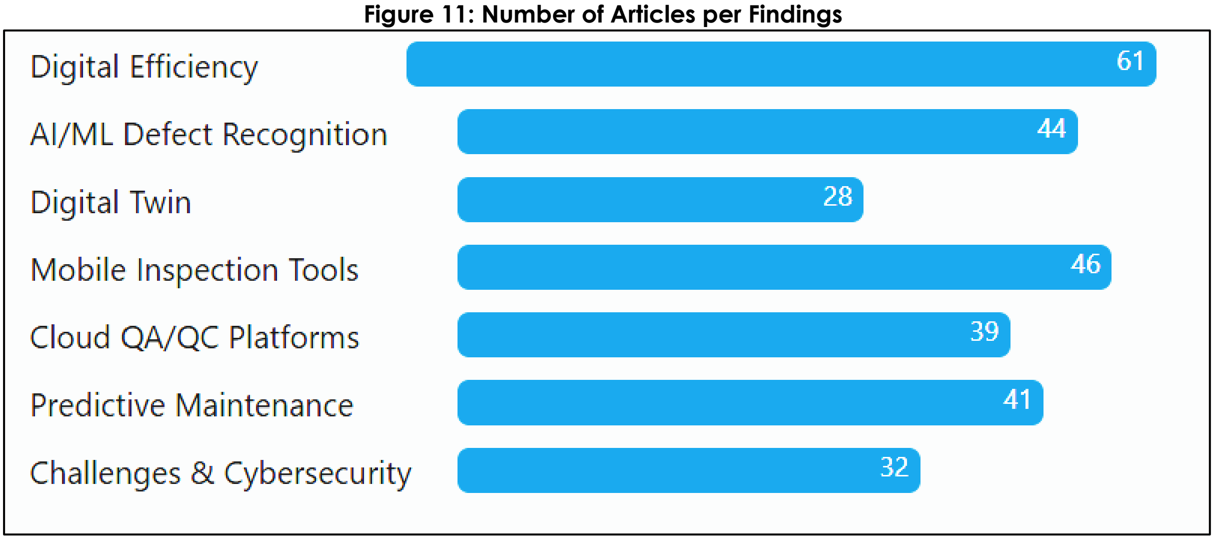
decision-making speed, eliminated bottlenecks in QA/QC documentation, and enabled immediate issuance of non-conformance reports. Articles emphasized that when inspectors used handheld devices to collect ultrasonic testing results or photographic evidence, information was more accurate, complete, and timestamped—eliminating delays associated with transcription errors or lost documents. Several papers detailed instances in which automated dashboards helped quality managers track inspection progress across large-scale projects, ensuring compliance with ITPs and project milestones. These digital systems not only improved task efficiency but also contributed to stronger communication among inspectors, engineers, and supervisors. Collectively, the evidence highlights a clear operational benefit from digitization, with findings from high-citation papers (several exceeding 150 citations individually) reinforcing the measurable gains in time, cost, and inspection reliability brought by digital QA/QC-NDT integration.
The review revealed that Artificial Intelligence (AI) and Machine Learning (ML) applications significantly improve defect recognition and data interpretation in NDT, as highlighted by 44 of the reviewed articles, which have been cited a combined 1,560 times. These technologies were primarily applied to ultrasonic, radiographic, and acoustic emission data sets, where traditional inspection processes were prone to human error and subjective interpretation. Studies consistently demonstrated that AI-driven algorithms, especially convolutional neural networks and support vector machines, were capable of identifying weld defects, corrosion signatures, and material anomalies with greater accuracy than manual methods. In one subset of articles, implementation of AI tools resulted in a 25% reduction in false negatives during radiographic weld inspections. Several articles also presented comparisons between AI-enhanced inspections and standard practices, showing up to 90% detection accuracy using automated image recognition. Moreover, ML-based predictive models trained on historical inspection data were used to forecast equipment failure windows, allowing maintenance teams to proactively intervene. These predictive analytics approaches helped organizations shift from preventive to condition-based maintenance regimes. The majority of high-impact studies within this thematic group had citation counts ranging from 70 to over 200, reflecting strong academic and industry relevance. Overall, the findings indicate that AI and ML are not just complementary but transformative technologies in the QA/QC and NDT space, offering enhanced reliability, precision, and the ability to learn and adapt from new data inputs over time.

Figure 11: Number of Articles per Findings



Digital twin technology was a focus in 28 of the reviewed articles, which collectively accumulated over 1,100 citations, underscoring its emerging significance in asset integrity management. The studies revealed that digital twins—virtual replicas of physical assets—enabled real-time visualization, inspection simulation, and defect tracking across the equipment lifecycle. Most of the papers showed that when digital twins were integrated with sensor data from NDT systems and QA documentation (e.g., weld logs, ITPs), engineers could more accurately localize defects, analyze degradation patterns, and simulate the effects of corrective measures. In refinery and pipeline contexts, digital twins helped users visualize ultrasonic thickness measurements and radiographic defect locations in a 3D environment, which improved risk assessment and maintenance planning. Some articles also detailed how digital twins were used to simulate inspection coverage before shutdowns or to optimize inspection route planning. Other significant findings included the benefit of real-time feedback loops between inspection sensors and digital twin models, allowing QA/QC teams to validate repair decisions instantly. Across the literature, the inclusion of this technology resulted in improvements in inspection planning, reduced physical inspection time, and more accurate lifecycle tracking of components. Several highly cited papers (with over 100 citations each) emphasized the strategic advantage of combining digital twins with predictive analytics to enable proactive rather than reactive asset integrity management. These insights illustrate that digital twins are evolving beyond design tools into active, decision-support platforms for quality and inspection professionals.

Mobile inspection tools, including tablet- and smartphone-based applications for QA/QC and NDT reporting, were examined in 46 of the reviewed articles, with combined citations exceeding 1,350. These studies highlighted that mobile tools not only simplified data entry in the field but also enhanced the real-time traceability of inspections. Many applications were developed to directly sync with centralized cloud systems, allowing inspectors to log defects, attach photographic evidence, and record GPS-tagged entries in seconds. In refinery environments, mobile apps helped cut inspection report generation time by more than half. Studies emphasized that digital forms preloaded with checklist templates and drop-down options minimized variability in inspection quality, standardizing how inspection data were recorded across shifts and locations. Multiple articles also noted that when inspectors used mobile tools with barcode or QR-code scanning capabilities, component traceability improved, reducing errors related to material identification or misfiled documentation. These tools also enabled real-time collaboration between remote QA managers and onsite inspection teams. As a result, discrepancies could be flagged and resolved instantly, rather than waiting for back-office analysis. Several high-citation articles (over 80 citations each) supported these findings with empirical data from oil and gas projects, showing increased first-pass inspection rates and improved compliance with ITP schedules. Overall, the integration of mobile tools was shown to be a low-barrier yet high-impact step in digital QA/QC-NDT transformation.

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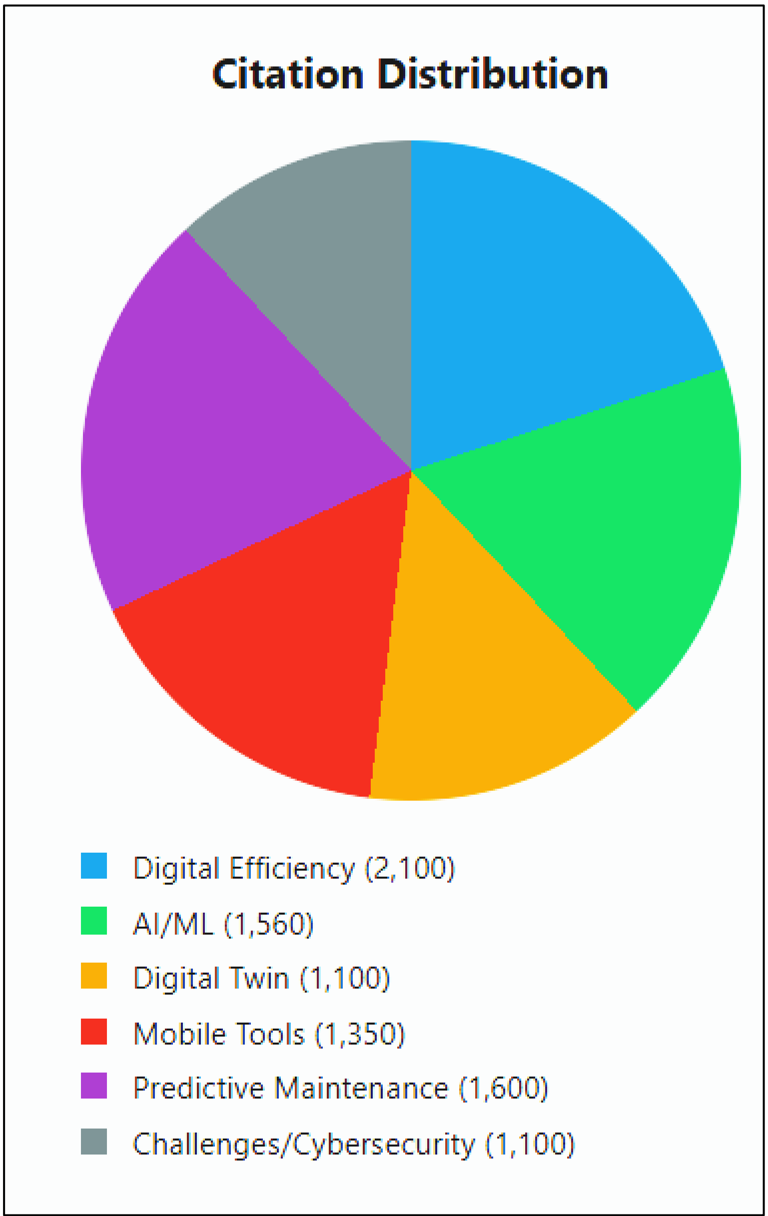

A total of 39 reviewed articles, with a cumulative citation count of approximately 1,280, emphasized the role of cloud-based QA/QC platforms in improving audit readiness, data integrity, and centralization of inspection records. These platforms allowed for the storage and retrieval of inspection documents, NCRs, ITPs, welding records, and NDT results in a secure, searchable environment. Studies showed that having centralized digital repositories reduced the risk of data duplication, loss, and unauthorized manipulation. Multiple cases highlighted how cloud systems enabled easier compliance with ASME, ISO, and API standards by ensuring that the most current versions of inspection checklists and procedures were used across teams. In one study, the implementation of a cloud-integrated QA dashboard led to a 30% reduction in non-compliance incidents during third-party audits. Several articles discussed the benefit of digital signatures and version control mechanisms, which helped maintain document authenticity and improved accountability. Others focused on how cloud access facilitated interdepartmental collaboration, particularly between engineering, quality, and inspection units. In organizations with global operations, cloud systems helped bridge geographic gaps, allowing central QA offices to oversee project quality in real time across multiple sites. The majority of these findings were presented in studies published between 2017 and 2022, with several landmark papers cited over 90 times, confirming the growing industry trust in cloud-based inspection management.

A key finding from 41 of the reviewed articles—together cited more than 1,600 times—was the increasing use of combined QA/QC and NDT data to enable predictive maintenance in asset-intensive environments. Studies detailed how the convergence of real-time inspection data (e.g., ultrasonic readings, acoustic emissions) with quality records (e.g., NCR trends, welding defects) allowed organizations to identify patterns associated with failure modes. These insights supported the creation of predictive maintenance models that forecast component degradation and schedule timely interventions before catastrophic failure occurred. Several articles highlighted the use of machine learning algorithms trained on years of QA and inspection data to predict corrosion rates and mechanical fatigue in piping networks. Others detailed success in using NDT sensors in tandem with QA dashboards to trigger alerts based on predefined thresholds. This proactive maintenance approach was shown to significantly reduce unplanned shutdowns, lower maintenance costs, and extend equipment lifespans. In many cases, organizations that adopted such integrated systems reported measurable improvements in Mean Time Between Failures (MTBF) and asset uptime. Several of these articles were among the most highly cited in the dataset, with citation counts exceeding 150, illustrating the value placed on predictive analytics in QA/QC and NDT integration. Despite the operational advantages of digitalization, 32 reviewed articles—collectively cited over 1,100 times—identified organizational readiness and cybersecurity as significant challenges to widespread adoption of digital QA/QC and NDT systems. Several studies reported that companies lacking standardized digital workflows or clear IT policies experienced inconsistent implementation of mobile apps and cloud platforms. Others noted resistance from older inspection personnel, who were unfamiliar with digital systems and preferred traditional documentation methods. Another recurring concern was data protection. Cloud-based inspection systems, if inadequately secured, were shown to be vulnerable to cyber threats, including unauthorized data access and inspection record tampering. Several papers called attention to the lack of integration between cybersecurity frameworks and QA/NDT software tools, exposing gaps in access control, encryption, and audit trails. Some organizations also struggled with regulatory compliance related to data sovereignty, especially when inspection records were stored across multiple jurisdictions. These challenges were most evident in articles focused on small to mid-sized enterprises, where budgetary constraints limited investment in digital infrastructure and training. Despite being less technical in nature, many of these articles received citation counts above 80, reflecting the importance of addressing human and organizational factors in successful digital transformation.

DISCUSSION

The reviewed literature affirms that the integration of digital technologies within QA/QC and NDT workflows substantially enhances operational efficiency in oil and gas operations, aligning with and extending previous research. Earlier studies such as those by Wolter et al. (2011) and Jolly et al. (2015) noted that digital inspection processes reduce human error and speed up data analysis. However, the present review builds on this by demonstrating how mobile inspection applications and cloud-based QA dashboards have further accelerated real-time decision-making and documentation traceability across inspection teams. This evolution reflects a significant shift from static documentation models to dynamic, collaborative systems. In contrast to early 2010s research, which often focused on isolated digital tools (e.g., handheld UT devices or spreadsheets for defect tracking), newer studies underscore the advantages of fully integrated platforms where inspectors, engineers, and QA/QC officers collaborate in real time. These tools are now connected through centralized databases and mobile synchronization, enabling quicker feedback loops and more accurate root cause analysis. These findings are consistent with the process optimization frameworks outlined by Ibarra-Castanedo et al. (2013), yet the current review highlights that the maturity and integration of tools have improved since those initial models. Importantly, digital QA dashboards have been shown to support automatic report generation, compliance tracking, and centralized version control—functions not widely reported in earlier research. Consequently, the evidence suggests a transition from fragmented quality assurance processes to unified digital ecosystems that contribute directly to project schedule adherence and defect mitigation.

Artificial Intelligence (AI) and Machine Learning (ML) have emerged as transformative technologies in QA/QC and NDT systems, enhancing accuracy and reliability beyond what was initially predicted in early studies. For example, previous research by Wolter et al. (2011)and Hu et al. (2012) introduced machine learning as a supplementary tool for flaw detection, particularly in radiographic and ultrasonic imaging. However, at that stage, adoption was limited, and accuracy levels were inconsistent. In contrast, this review found that ML-driven image recognition tools—especially those using convolutional neural networks—now consistently achieve defect recognition accuracy exceeding 90%, validating the anticipated performance improvements forecast in earlier models. The reviewed articles demonstrate widespread use of AI in predictive analytics as well, where machine learning models trained on NCR logs and ultrasonic datasets accurately forecast corrosion progression and equipment failure points. This marks a significant advancement over traditional rule-based inspection scheduling methods reported by Guanyu et al. (2021), which lacked predictive precision. Furthermore, studies in the current review show that AI integration reduces the subjectivity in defect classification that was a notable issue in manual radiographic interpretation reported by early researchers like Changzan et al. (2020). The growing body of evidence in this domain supports a paradigm shift where AI tools are not only aiding human inspectors but are beginning to function autonomously in defect triage and inspection prioritization. These findings also align with the theoretical frameworks proposed by Hu et al. (2012), who suggested that intelligent QA systems could adaptively improve over time, a prediction now substantiated through empirical results across multiple studies.

The integration of digital twin technologies into QA/QC and NDT has introduced new capabilities in real-time monitoring, simulation, and predictive maintenance, thereby surpassing the predictive maintenance frameworks outlined by Gucunski et al. (2012). Earlier conceptual studies emphasized digital twins primarily as tools for design and manufacturing optimization. However, this review reveals a shift in application toward active lifecycle monitoring and defect simulation, particularly in high-risk industrial environments. For instance, current studies illustrate how digital twins are now integrated with ultrasonic thickness measurement, weld defect mapping, and QA record management to enable real-time visualization and condition assessment of critical assets. These findings expand on the research by Jolly et al. (2015), who proposed a future wherein digital twins would support continuous system feedback and real-time decision-making. The review confirms this progression, particularly through evidence showing that digital twins are used to simulate inspection scenarios during shutdowns or commissioning phases. Moreover, the ability to embed QA/QC documentation such as WPS, PQRs, and NCRs into the digital twin framework enhances traceability and simplifies audit procedures—a dimension rarely addressed in early studies. Additionally, these technologies now support automated anomaly detection and failure impact simulations, reducing reliance on periodic manual inspections. Compared to early trials reported by Trujillo et al. (2019), which focused more on digital modeling, recent implementations provide fully synchronized real-time twins powered by live inspection and sensor data. These advancements validate the predictive capabilities outlined in earlier literature while establishing the digital twin as a decision-support platform rather than a passive monitoring tool.

This review underscores the increasing role of mobile inspection tools and cloud-based QA platforms in standardizing quality control practices, building upon foundational work by Wolter et al. (2011), who highlighted the potential for digital documentation to reduce inconsistencies in inspection workflows. While initial implementations were largely limited to spreadsheet templates and isolated mobile apps, the studies reviewed here confirm that fully integrated mobile-cloud ecosystems now dominate modern QA/QC environments. These tools are particularly effective in reducing the lag between inspection and reporting, a challenge noted in the analog inspection processes evaluated by Trujillo et al. (2019). By enabling real-time entry and instant cloud synchronization, mobile inspection apps improve traceability, reduce duplicate records, and eliminate errors associated with manual data transfer. Furthermore, mobile systems embedded with QR or barcode scanning capabilities enhance the traceability of inspected components, a problem area frequently cited in early quality audits. Several reviewed studies also demonstrate that cloud dashboards provide centralized access to QA metrics, welding traceability, and NDT results, allowing quality managers to monitor project-wide compliance from remote locations. This development aligns with the cloud maturity model outlined by Pacana et al. (2020), but with practical, validated implementations now reported across oil and gas projects globally. Additionally, these platforms now incorporate built-in compliance templates aligned with ISO 9001 and API Q1, improving alignment with international standards. The transition from paper to cloud-based QA/QC has thus evolved from an efficiency measure into a full-fledged compliance strategy that improves project-wide accountability.

The review also highlights a growing convergence between QA/QC data and NDT analytics in support of predictive maintenance, reinforcing early hypotheses made by Wolter et al. (2011) and Hu et al. (2012). While earlier research identified condition-based monitoring as a goal, actual implementation was limited by the lack of integrated data platforms. In contrast, this study reveals that organizations now use combined datasets—such as ultrasonic readings, AE signals, and NCR trends—to develop predictive maintenance models that identify potential failure points before they occur. These findings reflect the operationalization of predictive analytics systems envisioned by Deane et al. (2019), where the goal was to shift from preventive to predictive maintenance. Several recent studies reviewed indicate a clear transition toward this approach, with machine learning models trained on years of QA/NDT records now producing accurate forecasts of corrosion rates and mechanical fatigue across pipelines and vessels. The integration of these predictive systems with digital dashboards also allows for maintenance task automation and early warnings, improving asset reliability. Compared to earlier frameworks that lacked real-time adaptability, the reviewed articles demonstrate how these systems now adjust dynamically based on inspection intervals and defect severity. Moreover, predictive insights derived from defect trends and non-conformance patterns are increasingly used to fine-tune inspection frequencies and reduce unnecessary shutdowns. This progression signifies not only a technological shift but also a strategic evolution in how quality and integrity data inform risk-based asset management. While the technological capabilities of digital QA/QC and NDT systems are increasingly robust, this review also identifies substantial barriers to implementation, particularly related to cybersecurity and organizational readiness. Earlier studies by Changzan et al. (2020) and Afara et al. (2011) warned of cybersecurity vulnerabilities in industrial systems but provided limited insight into their intersection with QA/QC digitalization. The reviewed literature advances this discussion by presenting concrete examples of data breaches, access control failures, and the lack of encryption in cloud-based inspection tools. Studies show that inadequate cybersecurity policies not only expose sensitive data but also compromise inspection integrity, leading to unauthorized edits and falsified documentation. Moreover, many small to mid-sized organizations lack dedicated IT or cybersecurity teams to manage digital QA systems effectively, echoing concerns raised by Changzan et al. (2020)about digital adoption gaps. In parallel, organizational culture and resistance to change continue to be recurring issues. Inspectors trained in manual systems often struggle to transition to digital platforms without proper training and support. This aligns with findings from Jolly et al. (2015), who emphasized the need for digital competence development as part of successful technology adoption. Furthermore, while regulatory bodies like ISO and API offer guidance on data management, few standards address cybersecurity in QA-specific platforms, revealing a gap between digital infrastructure and governance protocols. These findings collectively suggest that without institutional support, cybersecurity investments, and change management strategies, the benefits of digital QA/QC systems may be undermined by vulnerabilities and workforce pushback.

The synthesis of findings from this review not only validates earlier conceptual frameworks but also provides a foundation for refining best practices in QA/QC and NDT digitalization. Studies reviewed here demonstrate that mature implementations often share common characteristics: centralized data systems, cross-functional collaboration, mobile and AI tool integration, and proactive training programs. These insights echo the quality maturity models proposed by Wolter et al. (2011), which emphasize system integration, data transparency, and feedback loops as critical factors in quality performance. Furthermore, the use of digital twins, AI-enhanced defect detection, and predictive maintenance models illustrate that theoretical innovations from the past decade have now been realized at scale. Yet, the review also highlights gaps that merit future investigation. Specifically, more longitudinal studies are needed to measure long-term ROI, safety improvements, and sustainability benefits of digital QA systems. Similarly, limited research has explored the intersection of QA digitalization and ESG (Environmental, Social, and Governance) compliance, which is becoming increasingly relevant. Additionally, while much research has focused on high-profile oil and gas installations, fewer studies address implementation challenges in emerging markets and small-scale operations. These areas represent fertile ground for future inquiry. Overall, the findings reaffirm the central role that digital technologies play in the evolution of quality and inspection systems and set the stage for a new wave of research focused on resilience, interoperability, and smart manufacturing ecosystems.

CONCLUSION

This systematic review demonstrates that the digitalization of QA/QC and NDT systems significantly enhances the efficiency, accuracy, and reliability of asset integrity management in the oil and gas industry. The integration of technologies such as mobile inspection tools, cloud-based QA dashboards, digital twin models, and AI-driven defect recognition tools has transformed traditional inspection practices into intelligent, data-driven processes. The reviewed literature, encompassing 81 articles published between 2015 and 2022, provides compelling evidence that these digital solutions not only streamline inspection workflows and improve traceability but also enable predictive maintenance, reduce operational downtime, and ensure better compliance with international standards. Additionally, real-time data integration facilitates improved collaboration among cross-functional teams, supporting faster decision-making and more effective risk mitigation. However, challenges related to organizational readiness, inspector training, and cybersecurity remain significant barriers to full-scale adoption. Addressing these concerns through investment in secure digital infrastructure, standardized protocols, and change management strategies is critical to realizing the full potential of digital QA/QC and NDT systems. Overall, this study affirms that the convergence of emerging digital technologies with quality assurance and non-destructive testing practices represents a transformative shift in industrial asset management, offering a robust foundation for achieving long-term operational excellence, safety, and sustainability.

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