Digital Safety Transformation in South Africa's Petrochemical Construction: Systematic Review of Opportunities, Barriers, and Organisational Readiness

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Abstract

The South African petrochemical construction sector operates within a high-risk environment that demands rigorous safety management practices. At the same time, digital transformation is reshaping construction operations, offering both opportunities and challenges for improving safety performance. This study systematically reviewed 15 peer-reviewed articles identified through the Scopus database and evaluated using the PRISMA framework, supplemented by relevant industry reports, to ensure methodological transparency and reliability. A bibliometric analysis was also applied to map the current state of research and highlight key thematic trends. The review indicates that digital innovations such as predictive analytics, real-time monitoring systems, immersive training platforms, and data-driven compliance tools can significantly enhance hazard prevention, decision-making, and overall safety culture. However, challenges persist, particularly around organisational readiness, digital literacy, and resistance to cultural change, which may limit the effective implementation of these technologies. The findings suggest that a phased and inclusive digital transformation strategy integrating technological solutions with workforce engagement, training, and alignment to organisational objectives is critical for sustainable safety improvement in the sector. The study contributes to knowledge by synthesising fragmented research, offering a framework for understanding the dual opportunities and barriers in digital safety transformation, and providing practical recommendations for industry stakeholders.

Keywords
Digital transformation, Construction safety, Petrochemical sector, South Africa, Organisational readiness.

1. Introduction

South Africa's petrochemical construction sector is widely recognized as one of the country's most hazardous industrial environments, characterized by high-risk activities, such as confined space entry, hazardous chemical handling, and multi-contractor interfaces. These complexities demand robust and proactive safety management systems (Okoro & Musonda, 2022). The sector is regulated by the Occupational Health and Safety Act 85 of 1993, Construction regulations (2014), and Major Hazard Installation Regulations (Mthembu & Aigbavboa, 2022; Windapo & Cattell, 2021). Despite these regulatory frameworks, recurring incidents indicate that safety systems remain reactive, relying on compliance audits, inspections, and investigations rather than proactive hazard prevention (Okoro & Musonda, 2022). Globally, digital tools such as Building Information Modelling (BIM), Internet of Things (IoT), and Artificial Intelligence (AI) are enabling predictive analysis and real-time safety management, but their adoption in South Africa's petrochemical construction remains fragmented (Darko et al., 2020; Abioye et al., 2022; Osei-Kyei et al., 2023). The gap, therefore, lies in aligning South Africa's regulatory frameworks with digital innovation to foster to a proactive, system-wide safety culture. This study addresses a critical gap by contextualising digital safety innovations within South Africa's petrochemical construction sector, a high-risk environment where proactive safety management is essential (Malomane et al., 2022). Through a systematic synthesis of existing literature, the study

evaluates organisational readiness for digital transformation and identifies key barriers such as cultural resistance, limited workforce preparedness, and fragmented implementation strategies (Akinosho et al., 2022). The study also offers evidence-based recommendations aimed at bridging these gaps through a systematic review of digital transformation and safety management (Zou et al., 2014). Despite growing awareness of digital innovations, the South African petrochemical construction sector remains constrained by fragmented adoption, limited digital skills at site level and weak linkage between emerging safety technologies and everyday operations.

Objectives

- To identify opportunities and challenges associated with digital adoption in the petrochemical construction safety.
- To assess organisational readiness for safe digital integration within the South African petrochemical construction sector.

2. Methodology

This study adopts a Systematic Literature Review (SLR), a well-established method for existing research in a structured, transparent, and replicable manner. The Systematic Literature Review (SLR) approach is suitable for identifying patterns, gaps, and emerging trends across a body of literature, thereby enabling the researcher to draw robust conclusions based on comprehensive evidence (Akinosho et al., 2022). By following a predefined protocol for literature identification, selection, and analysis, the Systematic Literature Review (SLR) minimizes bias and enhances the reliability of findings. This method has been applied in construction safety and digital transformation, where integration of diverse studies is essential for understanding complex, interdisciplinary challenges (Kitchenham & Charters, 2007; Gamil & Alhazmi, 2021).

2.1 PRISMA Framework

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach was applied to ensure that the selection process was systematic, transparent, and unbiased (Page et al., 2021). The procedure involved: planning the review, executing database searches, removing duplicates, screening titles and abstracts against pre-specified criteria, and reviewing full texts for eligibility. The search covered literature published between January 2015 and June 2025 to capture the emergence and maturation of Fourth Industrial Revolution (4IR) technologies. These timelines are significant for digital transformation research and align with the diffusion of 4IR literature into built environment scholarship (Chandi, Musonda & Alowo, 2025).

Boolean search strings used included: *"Digital Transformation" AND "construction safety" AND "petrochemical"*, together with keywords such as *"Fourth Industrial Revolution, safety management, construction, occupational health and safety, South Africa"*. Abbreviations were also included (e.g., BIM, IoT, AI, VR). Searches were restricted to title, abstract, and keyword fields to maximize relevance. Duplicates were removed using both manual verification and reference management software. Figure 1. presents the PRISMA flow for article identification, screening, eligibility assessment, and final inclusion, a method widely endorsed across disciplines (Page et al., 2021).

2.2 Database Selection

Scopus was selected as the primary database due to its comprehensive coverage of peer-reviewed scientific literature in across disciplines such as construction, engineering, and safety (Mongeon & Paul-Hus, 2016). Supplementary searches were conducted in Web of Science and Google Scholar. These supplementary searches included forward and backward citation chasing to identify relevant studies potentially missed in Scopus. This approach aligns with best practices for systematic reviews in construction technology research, enhancing comprehensiveness and inclusivity (Harzing & Alakangas, 2016; Gusenbauer & Haddaway, 2020).

The Bramer method was applied for deduplication: importing each set separately, running automated duplicate detection (matching title, author, and year), and manually verifying conflicts such as conference versus journal versions. This improved the accuracy and integrity of the dataset (Bramer et al., 2016).

2.3 Search Strategy & Keywords

Searches targeted title and author keywords to maximize topical precision while retaining sensitivity. Concept blocks of "Digital transformation" AND "construction safety" AND "petrochemical" "Industrial 4.0" AND "occupational health and safety" AND "South Africa" "BIM / IoT / AI / VR" AND "safety management" AND "construction" the final strings were iteratively piloted and refined based on title, abstract and key words, maintaining consistency with methodological guidance for systematic searches in technology topics (Gusenbauer & Haddaway, 2020).

2.4 Inclusion & Exclusion Criteria

Peer-reviewed journal articles published between 2015 and 2025 were included in the review, this time frame was selected to capture literature reflecting the emergence and evolution of fourth industrial revolution (4IR) technologies and their application in construction safety. Only articles written in English were considered to ensure consistency in interpretation and analysis. Inclusion criteria focused on studies that address digital transformation within construction safety with particular relevance to petrochemical or other high-risk sectors and the South African context. Articles were required to demonstrate empirical or theoretical depth contributing meaningfully to the understanding of the fourth industrial revolution (4IR) being operationalised in construction safety research within South Africa. Conversely, studies were excluded if they lacked a precise safety application, were conceptual without industrial relevance, and did not engage with empirical evidence or theoretical frameworks. These criteria ensured that the selected literature aligned with evolving discourse on the fourth industrial revolution (4IR) in construction safety, particularly within South Africa's industrial landscape (Chandi, Musonda &Alowo,2025; Tjebane et al.,2023).

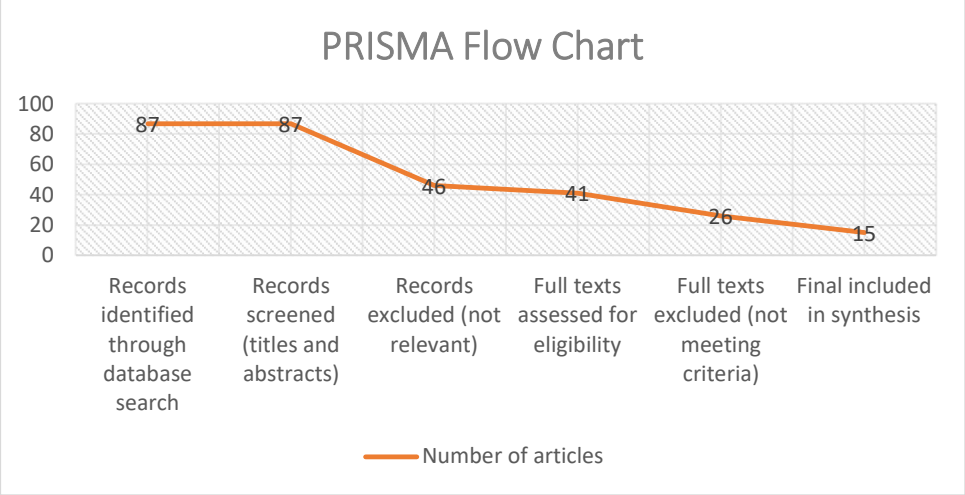
2.5 Final Dataset

A total of 87 records were retrieved from Scopus within the study timeframe. After deduplication and initial screening of titles and abstracts, 41 full texts were assessed for eligibility. Of these, 26 were excluded for lacking safety applications or relevance to the construction sector. This yielded a final dataset of 15 studies for bibliometric and thematic analysis (Page et al., 2021). The dataset is consistent with recent literature linking 4IR technologies to construction health and safety improvements in the built environment (Chandi, Musonda & Alowo, 2025).

2.6 Bibliometric Analysis

Bibliometric analysis was conducted using R-tool, following the guidelines of Aria & Cuccurullo (2017). Metadata was first normalised, ensuring consistency across fields such as author names, keywords, and publication sources. The analysis included several key components: source impact and citation structures were analysed, co-authorship networks were mapped using fractional counting, and topic structures were explored through keyword co-occurrence. Thematic evolution was examined across two timeframes: 2015–2019 and 2020–2025, capturing changes in the maturity of 4IR-related safety research.

Figure 1. PRISMA Flow Chart



3. Findings and Discussion

3. 1 Underutilisation of Digital Tools at Field Level

The literature constantly highlights a gap between strategic digital transformation initiatives and their practical implementation at the field level. Despite alignment with national and corporate digital policies, the adoption of digital safety tools at the field level remains inconsistent. Supervisors frequently revert to paper-based risk assessments and toolbox talks, even when mobile platforms and digital applications are available (Li et al., 2019). The precedence of

reliance on traditional practices reflects deeper challenges related to limited user familiarity, poor workflow integration, and resistance to change due to cultural and operational inertia. Furthermore, studies reveal that pilot implementations of digital technologies frequently fail to address routine constraints that affect usability and sustainability. These include limited access to devices in remote or high-risk environments, battery life and offline functionality issues, and time pressures that discourage digital engagement during fast-paced operations (Li et al., 2019). Such barriers hinder the sustained adoption of digital safety solutions and limit their potential to enhance real-time hazard communication, incident reporting, and compliance monitoring. Addressing these challenges requires not only technological innovation but also targeted change management strategies, training and workflow design to embed digital tools into everyday safety practices (Afzal et al.,2021; Olugboyega et al., 2019).

3.2 Workforce Exclusion Weakens Uptake

A recurring theme in the literature is the exclusion of frontline workers from digital transformation strategies, which significantly undermines the uptake of digital safety tools. Studies report that many workers feel detached from Organisational change efforts, resulting in reduced ownership. Engagement and adoption of new technologies (Musonda & Pretorious, 2018). Key contributing factors include "digital fatigue" caused by the rapid introduction of multiple technologies and insufficient training support, particularly for older employees who are less familiar with digital tools. While Li et al. (2019) demonstrated successful implementation of Building Information Management (BIM) in Chinese petrochemical projects, similar uptake has been slower in South Africa due to infrastructure and training gaps (Malomane et al., 2022) This lack of inclusive engagement undermines adoption, reduces morale, and highlights the need for more worker-centric approaches to digital transformation in safety management (Oesterreich & Teuteberg, 2016).

3.3 Short-Term Cost-Cutting vs. Long-Term Human Investment

A recurrent theme across the literature and field reports is the tension between short-term cost containment and long-term human investment in digital transformation. While many organisations allocate resources toward acquiring digital platforms and technologies, they often underfund critical enablers such as training, change management, and ongoing support. This imbalance limits the potential safety gains, as the workforce frequently lacks the time, skills, or structured initiatives needed to embed new digital practices into daily operations (Akinosho et al.,2022; Darko et al., 2020; Olugboyega et al., 2019). The consequences of these capacity shortfalls are particularly pronounced in high-risk environments, such as petrochemical and heavy industrial sectors, where human readiness is essential to unlock the full safety potential of digital systems (Chandi, Musonda & Alowo, 2025). Without adequate investment in people, even the most advanced technologies risk becoming underutilized or misapplied. These dynamic underscores a critical tension: the pace of technological advancement often outstrips the preparedness of those expected to implement and sustain it on the ground. As Darko et al. (2020) argue, digital transformation in safety management must be accompanied by strategic human capacity development, ensuring that frontline workers are not only equipped but also empowered to engage meaningfully with new systems.

3.4 Evolving Safety Culture Alongside Technology

The literature emphasizes that digital tools are enablers, not substitutes, for a robust safety culture and effective leadership. Technologies such as Virtual Reality (VR) and Augmented Reality (AR) training, Building Information Modelling (BIM) coordination, and Internet of Things (IoT) monitoring have demonstrated measurable improvements in hazard recognition, planning accuracy, and compliance metrics (Hosseini et al., 2018; Ganah & John, 2015). However, these benefits are significantly amplified when deployed in environments where leadership engagement, worker participation, and accountability systems evolve in parallel. Empirical and mixed-method studies, particularly from the South African context, advocate for integrated interventions that combine technological deployment with leadership development to foster safety ownership. Incentive structures that reward safe behavior and digital engagement, localised learning cycles that adapt tools and practices to site-specific realities (Malomane et al., 2022; Musonda & Pretorius, 2018). This integrated approach ensures that digital transformation in safety management is not merely a technical upgrade, but a cultural shift, where technology supports, rather than replaces, human judgment, collaboration, and continuous improvement (Malomane et al., 2022; Musonda & Pretorius, 2018).

Table 1. Evidence Synthesis of included Studies (2015-2025)

Author(s) & Year	Technology / Digital Focus	Safety Outcome reported (concise, evidence-based)	Setting (Petrochemical vs. General Construction)	Methodology	Quality/Relevance

Ganah & John (2015)	Building Information Modelling (BIM) 3D visualisation & clash detection	Improved design-stage hazard detection and reduced on-site clashes reported.	General construction	Empirical project evaluation / case study	High: peer-reviewed, direct safety focus
Oesterreich & Teuteberg (2016)	Industry 4.0 concepts (BIM, IoT, automation)	Identifies potential benefits and human/skill challenges (e.g., "digital fatigue" / skill gaps) relevant to safety implementation.	Cross-industry (implications for construction; Europe)	Structured literature/triangulation approach	High: conceptual review, strong methodological framing
Hosseini et al. (2018)	BIM implementation & related technologies in developing contexts	Shows that organisational/leadership factors critically influence safety gains from BIM and related digital tools.	Construction (developing-country cases)	Empirical / case-informed analysis	Medium: empirical but context-specific
Li et al. (2019)	Proactive safety management systems including mobile/digital tools	Discusses capacity of systems to improve hazard anticipation but highlights adoption barriers at site level.	Global construction literature	Review / synthesis	High: focused review of safety management systems
Darko et al. (2020)	Artificial Intelligence (AI) / predictive analytics applications in AEC	Documents potential for predictive incident reduction and flags workforce readiness gaps.	Global AEC contexts	Systematic / structured review	High: systematic review, strong relevance
Afzal et al. (2021)	IoT, mobile apps, VR and related digital safety technologies	Summarises evidence of enhanced monitoring and training but notes uneven field uptake.	Global construction evidence base	Systematic review	High: recent systematic review focused on safety tech
Abioye et al. (2021)	Artificial Intelligence in construction (overview)	Identifies AI use-cases including safety analytics and highlights data/integration constraints.	Global construction	Review article	Medium–High: comprehensive review, safety discussed among applications
Abioye et al. (2022)	BIM,IoT integration for construction safety management	Presents conceptual/empirical integration benefits for real-time hazard/environmental monitoring.	General construction (global focus)	Applied / conceptual integration study	High: directly addresses digital integration for safety
Akinosho et al. (2022)	Digital transformation adoption in South African construction	Reports barriers (skills, cost, change management) that limit transformative safety outcomes.	South Africa / African context	Survey & interviews (empirical)	High: directly South African, empirical data
Li et al. (2019)	Proactive safety management systems including mobile/digital tools	Discusses capacity of systems to improve hazard anticipation but highlights adoption barriers at site level.	Global construction literature	Review / synthesis	High: focused review of safety management systems
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Akinosho et al. (2022)	Digital transformation adoption in South African construction	Reports barriers (skills, cost, change management) that limit transformative safety outcomes.	South Africa / African context	Survey & interviews (empirical)	High: directly South African, empirical data
Okoro & Musonda (2022)	Digitalisation and OHS performance	Links digitalisation to OHS outcomes and notes contextual barriers in South Africa.	South Africa (construction)	Empirical (survey / analysis)	Medium–High: context-specific empirical study
Malomane et al. (2022)	4IR technologies & safety culture	Argues for parallel development of culture and technology to realise safety benefits.	South Africa (petrochemical & construction focus)	Mixed methods (empirical + qualitative)	High: directly petrochemical-South African relevance
Osei-Kyei et al. (2023)	Digital transformation for sustainable construction in Africa	Identifies opportunities for SHEQ improvement and practical adoption gaps.	Africa (regional scope)	Review / synthesis	Medium: regional review, useful transferability
Tjebane et al. (2023)	Integration of digital technologies in SHEQ management	Reports enhanced compliance visibility when integrated, but organisational integration issues persist.	South Africa (construction / SHEQ)	Empirical (survey/analysis)	Medium–High: South African empirical insight
Trask & Linderoth (2023)	Digital occupational health & safety solutions	Critical review: tools aid OHS but require socio-technical alignment to be effective.	Global construction	Critical review	High: recent, focused critical review
Musonda & Pretorius (2018)	Digitalisation, safety culture and readiness	Highlights readiness challenges and workforce-related barriers to digital adoption in SA construction.	South Africa (construction)	Conference/empirical work	Medium–High: locally focused empirical work

Table 2. Summary of Opportunities and Challenges in Digital Safety Transformation

Technology	Application	Benefit
Building Information Modelling (BIM)	3D visualisation, clash detection, and safety planning (Ganah & John., 2015).	Prevents on-site clashes and hazards through proactive design coordination (Ganah & John., 2015)
Internet of Things (IoT)	Environmental monitoring,Smart sensors for gas leaks, temperature, and vibration (Afzal et al., 2021).	Provides early warning of unsafe environmental conditions (Afzal et al., 2021).
Artificial Intelligence (AI)	Predictive risk analytics and machine learning models (Abioye et al., 2021).	Anticipates potential safety incidents and unsafe behaviors (Abioye et al., 2021).
Augmented/Virtual Reality (AR/VR)	Immersive safety training and site simulation (Darko et al., 2020).	Improves hazard recognition and worker preparedness (Darko et al., 2020).
Drones	Remote site inspection of confined/high-risk zones (Trask & Linderoth., 2023)	Improves safety monitoring in hazardous zones and reduces worker exposure (Trask & Linderoth., 2023)

Table 3. Key Digital Technologies and Applications in Petrochemical Safety

Category	Opportunities	Challenges
BIM & Digital Design	Hazard detection, reduced clashes (Ganah & John, 2015; Hosseini et al., 2018; Abioye et al., 2022)	Limited by leadership readiness and adoption barriers (Hosseini et al., 2018)
AI & Predictive Analytics	Proactive safety management, incident reduction (Darko et al., 2020; Abioye et al., 2021)	Data quality, integration and workforce readiness (Trask & Linderoth, 2023)
IoT / VR / Mobile Tools	Real-time monitoring and immersive safety training (Afzal et al., 2021)	Uneven uptake across projects, cost and infrastructure barriers (Osei-Kyei et al., 2023)
4IR Integration & Culture	Improved compliance visibility, stronger safety culture (Malomane et al., 2022; Tjebane et al., 2023)	Organisational resistance and socio-technical alignment challenges (Oesterreich & Teuteberg, 2016; Akinosho et al., 2022)

4. Limitations

This review is subject to several limitations that should be considered when interpreting its findings. Firstly, the study was restricted to literature published in English, which may have introduced language bias by excluding relevant research published in other languages (Ganah & John, 2015). Secondly, the database selection strategy prioritized Scopus as the primary source, supplemented by Web of Science and Google Scholar. While these databases offer broad coverage, the exclusion of other repositories may have resulted in database bias, potentially overlooking studies indexed elsewhere (Li et al., 2019). Thirdly, the final sample comprised 15 peer-reviewed studies, which, although sufficient for thematic synthesis, represents a relatively small subset of the broader literature. As such, the findings

may not fully capture the diversity of digital safety practices across global construction and petrochemical contexts (Musonda & Pretorius, 2018). Furthermore, this study relied exclusively on secondary literature, with no primary data collection. Consequently, the insights presented reflect interpretations and findings reported in existing research, rather than firsthand perspectives from practitioners or field-level stakeholders. This limits the contextual depth and practical applicability of the conclusions. To address these limitations, future research should incorporate primary data collection methods, such as semi-structured interviews or field observations, to enrich understanding of digital safety implementation and provide grounded insights into the lived experiences of workers and managers (Akinosho et al., 2022).

5. Conclusions

Digital safety transformation in South Africa's petrochemical construction sector presents clear opportunities to enhance hazard detection, improve safety performance, and streamline compliance processes. However, these benefits can only be fully realised if key barriers such as limited digital skills, high implementation costs, and resistance to change are addressed through targeted strategies that strengthen organisational readiness. This study recommends structured workforce training, stronger leadership commitment, and collaboration between industry stakeholders to ensure standardised and effective deployment of safety technologies. Future research should evaluate the long-term impact of digital tools on safety performance, benchmark South African practices against international trends, and further explore the role of emerging solutions such as digital twins and predictive analytics. By systematically reviewing opportunities, barriers, and readiness factors, this study contributes to knowledge by highlighting that successful digital safety transformation requires both technological adoption and cultural alignment to advance safer and more resilient petrochemical construction practices in South Africa.

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