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A Hybrid Theoretical Framework for Technology Adoption in the Construction Industry

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Abstract

This study investigates the determinants of Fourth Industrial Revolution (4IR) technology adoption in the South African construction industry, a sector critical for employment and infrastructure development in a high-unemployment economy. Guided by an integrated Technology-Organization-Environment (TOE) and Technology Acceptance Model (TAM) theoretical framework, the research adopts an interpretivist philosophy and qualitative methodology to explore the complex interplay of technological, organizational, and environmental factors shaping adoption. The qualitative research employed semi-structured interviews with 15 directors and office managers from CIDB Grade 9 contractors and major consulting engineering firms, selected via purposive sampling. Data were analyzed using inductive thematic analysis following Boyatzis (1998), yielding eight themes: limited 4IR awareness, sectoral readiness due to skills gaps and infrastructure deficits, fragmented client-driven adoption, absent training programs, concerns over job displacement, and inadequate government policy. Findings reveal that adoption is constrained by a lack of organizational readiness, acute skills shortages, infrastructural deficits, high costs, and socio-political fears of job displacement, alongside entrenched cultural resistance to change. Furthermore, the studies reveal a vicious inertia cycle exacerbated by socio-political pressures to preserve low-skilled employment in a high unemployment context, overriding perceived ease of use and benefits. While awareness of 4IR benefits exists, actual implementation remains fragmented and confined largely to large firms and urban centers. The study contributes a contextualized, multi-level adoption framework tailored to South Africa's unique socio-economic landscape, offering evidence-based recommendations for policymakers, industry leaders, and educators to foster an inclusive and sustainable digital transformation that balances technological modernization with equitable employment outcomes.

Keywords
Fourth Industrial Revolution, Technology Adoption, TOE, TAM, Construction

1. Introduction
This study focuses on the theoretical and empirical literature on the adoption of technology in the construction sector, with specific focus on the South African Construction Industry/Sector. The study commences with a discussion of the Technology-Organization and Environment, the theoretical framework as the foundational perspective for investigating factors shaping the adoption of technology in the sector. The key concepts of the framework, its empirical application and limitations are discussed and the context for the application of the framework to the present study. The theoretical review is followed by the empirical review of the literature organized according the research objectives. The existing gaps in the current research are discussed thus positioning the present study in the extant body of literature. The Fourth Industrial Revolution (4IR), often referred to as Industry 4.0, originated in Germany in 2011 as a vision for creating intelligent, interconnected production systems through cyber-physical systems (CPS), the Internet of Things (IoT), artificial intelligence (AI), and robotics (Zhong et al., 2017). This paradigm has evolved to encompass digital twins, which are virtual replicas of physical assets that enable real-time simulation, monitoring, and optimisation through sensors and IoT connectivity (Zhong et al., 2017). Beyond manufacturing, 4IR is reshaping

organisational structures, business models, and value chains across sectors by integrating data-driven decision-making and automation (Nowotarski & Paslawski, 2017; Tjahjono et al., 2017). Recent advancements, such as AI-powered predictive analytics and Blockchain for secure supply chain tracking, have further amplified these capabilities, promising enhanced efficiency and sustainability in complex project lifecycles. Several industries have swiftly embraced 4IR innovations, including digitised financial services in banking, drone-enabled precision farming in agriculture, and robotic-assisted surgeries in healthcare (Kruger & Steyn, 2024; Mhlanga & Ndhlovu, 2023). However, the construction sector remains notably behind in this transformation, particularly in developing economies like South Africa (Alade & Windapo, 2020). A 2023 review of 4IR-related research in the South African construction industry underscores this lag, revealing that while awareness of technologies like Building Information Modelling (BIM), unmanned aerial vehicles (UAVs), and big data analytics exists among professionals, actual implementation is sporadic and confined primarily to early project stages such as design and feasibility (CIDB, 2023). For instance, IoT and cloud computing see moderate uptake for cost control, but only about 26% of firms engage in digital tendering processes, with small and medium enterprises (SMEs) disproportionately excluded due to resource constraints (CIDB, 2023). The South African construction industry's labour-intensive nature, which supports high employment but perpetuates outdated practices, exacerbates this reluctance (Pinfold & Fapohunda, 2016). Recent studies affirm the dual-edged impact of 4IR: while it drives productivity gains in energy savings in green buildings through smart meters, building management systems (BMS), and AI-optimised ventilation, adoption remains limited to premium, green-rated projects due to prohibitive capital costs and regulatory gaps (Kissi et al., 2023; Van der Merwe & Davey, 2024). Technologies such as robotics and digital twins could revolutionise real-time monitoring, reduce accidents by automating hazardous tasks, and foster circular economy principles by minimising waste and emissions (Begić & Galić, 2021). Yet, these benefits are overshadowed by socioeconomic risks, including job displacement for low-skilled workers, potentially affecting 40-50% of roles in African contexts, and skills mismatches that leave employees struggling to adapt to rapid technological shifts (Abdullahi et al., 2020; Mohd Abas et al., 2019). Although awareness of 4IR technologies is increasing within the South African construction sector, adoption remains fragmented, inconsistent, and largely confined to selected project phases (Begić & Galić, 2021; Pinfold & Fapohunda, 2016). Existing research identifies common barriers such as high implementation costs, limited digital skills, resistance to change, and weak regulatory pressure (Van der Merwe & Davey, 2024). However, these studies remain largely descriptive and fail to systematically examine how technological characteristics, organisational readiness, and environmental pressures interact to influence adoption behaviour (Begić & Galić, 2021; Mhlanga & Ndhlovu, 2023; Mohd Abas et al., 2019; Pinfold & Fapohunda, 2016). This study responds to that gap by developing and applying a context-specific Technology–Organisation–Environment (TOE) adoption framework to examine the determinants of 4IR technology adoption among CIDB Grade 9 construction firms in South Africa.

1.1 Objectives

The primary objective of this study is to develop a contextualized framework that explains the multi-level determinants of 4IR technology adoption in the South African construction industry.

a) To analyze the interdependent roles of awareness, skills availability, and perceived organizational capability as a combined construct, and to assess their varying impact on the adoption potential across different segments of the industry.
b) To evaluate how the perceived characteristics of 4IR technologies (for example, ease of use, compatibility, relative advantage) are moderated by the specific operational and resource realities of South African firms, and to identify which characteristics are most critical for adoption in this context.
c) To investigate the mediating role of stakeholder attitudes, with a specific focus on the perceived socio-economic impact of automation, in shaping the adoption pathway from intention to implementation.

2. Literature Review

To comprehensively explain organizational and individual acceptance of complex, disruptive technologies such as BIM, drones, and augmented reality, this study adopts a hybrid Technology–Organization–Environment (TOE) and Technology Acceptance Model (TAM) framework. While the TOE framework (Tornatzky and Fleischer, 1990) excels at capturing macro-level organizational and external influences, the Technology Acceptance Model (TAM) (Davis, 1989; Davis & Venkatesh, 1996) provides deeper insight into individual-level behavioral determinants—particularly perceived usefulness (PU) and perceived ease of use (PEOU)—that ultimately drive acceptance within organizations. Hybrid TOE-TAM models have gained prominence in construction and 4IR adoption research because neither framework alone fully accounts for the multifaceted reality of technology implementation in project-based, fragmented, and socio-economically sensitive sectors (Na et al., 2022; Sepasgozar & Davis, 2018). In these integrated models, the Technology context (TOE) is enriched by TAM's perceived usefulness and perceived ease of use, reframing relative advantage and complexity through the lens of user perception. Organization context (TOE) incorporates internal readiness factors (resources, leadership support, digital culture, skills) that mediate how perceived usefulness and ease of use translate into actual adoption. Environment context (TOE) includes external pressures (client demands, regulatory frameworks, competitive intensity) that moderate both organizational readiness and individual attitudes. This literature review employs a hybrid TOE-TAM framework as its core theoretical foundation.

Technology-Organization and Environment Model (TOE)

The three TOE contexts (Technology, Organization, and Environment) form the structural foundation. TAM's two core constructs, Perceived Usefulness (PU) and Perceived Ease of Use (PEOU), are embedded as mediating mechanisms that translate contextual factors into behavioral intention and actual adoption. In the South African construction setting, PU is strongly shaped by client demands and perceived efficiency gains, while PEOU is heavily moderated by skills shortages, poor digital infrastructure, and the absence of training. Organization context acts as the central mediator because resource availability, leadership commitment, and socio-political concerns (especially fear of job losses) determine whether perceived benefits are realized. Arrows indicate bidirectional influence: individual perceptions affect organizational decisions, and external pressures filter through organizational readiness.

This adapted hybrid TOE-TAM framework developed from (Ametepey et al., 2024; Davis, 1989; Na et al., 2022; Tomatzky & Fleischer, 1990) provides the analytical lens through which the empirical findings of this study are interpreted and the final context-specific model is proposed in Figure 1.

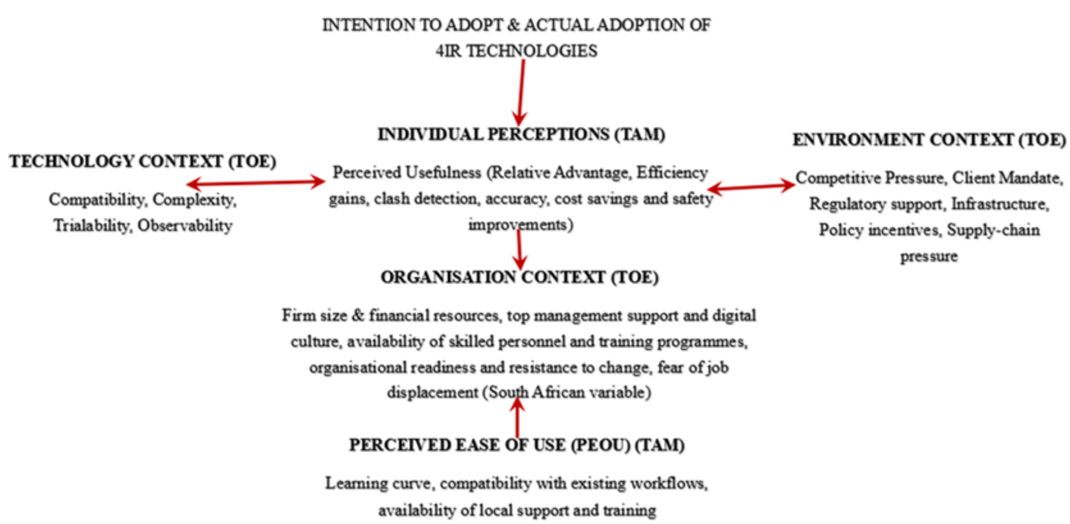

Figure 1. Hybrid TOE-TAM Theoretical Framework. Source: Author's Compilation from Theoretical Literature (Tornatzky & Fleischer, 1990; Davis, 1989)

The Technology–Organization–Environment (TOE) framework, developed by Tornatzky and Fleischer (1990), has evolved into one of the most influential models for analyzing organizational technology adoption. Baker (2012) formalized and clarified its conceptual structure, emphasizing that technology adoption is shaped by three contextual domains: (1) technological characteristics, (2) organizational readiness, and (3) environmental pressures. Baker's exposition established TOE as a holistic, multi-level framework that balances internal and external determinants of adoption (Baker, 2012). Its core proposition is elegantly straightforward: an organization's adoption and implementation of a technological innovation are influenced by a combination of factors nested within three interconnected contexts—the Technological context, the Organizational context, and the Environmental context (Baker, 2012). The Technological context refers to the characteristics of the available technologies, both internal and external to the firm, such as their relative advantage, compatibility, and complexity. The organizational context encompasses the firm's internal attributes, including its size, structure, managerial support, and resource slack. The Environmental context represents the arena in which the firm conducts its business, including industry characteristics, competitive pressures, regulatory policies, and the availability of external technological support (Al Hadwer et al., 2021; Awa et al., 2016; Chong & Olesen, 2017).

The framework's longevity is a testament not to stasis, but to its dynamic evolution, as evidenced by the body of literature synthesized in this review. Its development can be charted along three key trajectories: conceptual enrichment and integration, domain expansion, and methodological refinement. First, scholars have consistently worked on conceptual enrichment and integration, enhancing the framework's explanatory power (Awa et al., 2016; Tsou & Hsu, 2015; Wu & Chen, 2014). Early on, researchers like Al-Zoubi (2013) demonstrated TOE's compatibility with other theories, integrating it with Rogers's Diffusion of Innovation to bridge individual perception and organizational context. This integrative approach was later championed by Awa, Ukoha and Igwe (2017), who explicitly argued for TOE's "enriched applicability" through synthesis with models like UTAUT.

TOE Framework in Empirical Literature

The Architecture, Engineering, Construction, and Operations (AECO) sector, alongside related manufacturing and urban planning industries, stands at a critical juncture. Driven by the forces of the Fourth Industrial Revolution (4IR), these industries are under immense pressure to adopt digital technologies, from Building Information Modelling (BIM) and robotics to the Internet of Things (IoT) and artificial intelligence (AI), to improve productivity, sustainability, and competitiveness. However, as evidenced by the body of literature, adoption remains fragmented, slow, and fraught with challenges, particularly in developing economies and among small and medium-sized enterprises (SMEs). Compared to other sectors, construction remains one of the slowest adopters of advanced technologies. Scholars widely attribute this lag not to irrational resistance but to a complex interplay of technological, organizational, and environmental factors that collectively shape adoption behavior (Al Hadwer et al., 2021; Begić & Galić, 2021; Tsou & Hsu, 2015). Explaining this complex phenomenon requires a theoretical lens that moves beyond purely individual or technological determinism to account for the multifaceted context of firms and industries. The Technology-Organization-Environment (TOE) framework, initially proposed by Tornatzky and Fleischer (1990), provides a robust theoretical foundation for analyzing this complexity. The TOE conceptualizes technology adoption as a multi-context process shaped by (1) technological readiness and characteristics, (2) organizational capacity and culture, and (3) external environmental pressures and enablers. Given construction's fragmentation, project-based nature, and interdependence among multiple stakeholders, the TOE framework has become one of the most widely applied models in construction technology adoption research.

The TOE-TAM Model

The integration of the Technology Acceptance Model (TAM) with the Technology–Organization–Environment (TOE) framework has become one of the most widely adopted theoretical lenses for explaining organizational and individual-level technology adoption in the past decade (Gangwar et al., 2015). Originating with Gangwar, Date, and Ramaswamy's (2015) highly influential study on cloud computing adoption (cited more than 1,600 times), the hybrid TOE-TAM model deliberately bridges the micro-level focus of TAM on perceived usefulness and perceived ease of use with the macro-level emphasis of TOE on technological, organizational, and environmental contexts. Subsequent studies built on Gangwar et al.'s (2015) insights by applying the hybrid model to diverse organizational contexts. In SMEs, Truong (2022) used TOE–TAM to model digital transformation adoption, demonstrating that SMEs' adoption decisions depend on organizational support, leadership culture, technological infrastructure, and perceptions of usefulness (Truong, 2022). Similarly, Nawaz and Thelijjagoda (2025) applied a TOE–TOE-TAM-informed SEM–ANN approach to cloud computing adoption among Sri Lankan SMEs. Their findings emphasized that technological readiness, ICT skills, and environmental pressures strongly determine adoption and improve SME performance (Nawaz & Thelijjagoda, 2025). In online retail transformation, Nguyen et al. (2022) extended the TOE framework and complemented it with acceptance principles aligned with TAM to tailor adoption modelling to digital retail environments. The extended model captured market dynamics, customer pressure, and the compatibility of digital retailing tools.

3. Methods

Thematic analysis of qualitative data sourced from construction industry participants from CESA member firms and CIDB grade 9 construction firms.

4. Data Collection

Interviews were conducted on 15 research participants. The interview guide questions were split into two sections, A and B. Section A focused on demographics questions such as geography location, position in the firm and the company classification whether it is a CIDB grade 9 firm or a CESA registered firm. Meanwhile section B focused on the following questions; (1) Explain the fourth industrial revolution in terms of your knowledge and understanding. (2) Do you think the construction sector in South Africa is ready for the fourth industrial revolution? (3) Which of the 4IR technologies have you adopted and why? (4) Describe the 4IR Technology training programmes your organization provides for its staff if any. (5) Is it easier to use the 4IR technologies than to use the conventional approach in construction? (6) What are your perspectives towards the notion that: 4IR technologies adoption will replace human jobs? (7) What are your perspectives on Government Policy towards promotion of the fourth industrial revolution in construction? Interviews were conducted on virtual meeting platforms and automatic transcriptions were performed using Tactiq.

5. Results and Discussion

A total of 15 participants were interviewed, yielding a robust sample for qualitative analysis. Key demographic attributes were captured consistently across transcripts. All 15 participants (100%) confirmed their firms are based in South Africa. This aligns with the study's focus on domestic adoption patterns within the local construction industry. Participants held senior leadership or managerial roles, reflecting decision-making authority over technology adoption in Table 1 and Table 2.

Table 1. Position in Firm

Position Category	Participants	Frequency	Percentage
Director/CEO/Equivalent	1, 2, 4, 5, 7, 8, 9, 10, 11, 14, 15	11	73.3%
Office Manager	3	1	6.7%
Other (Senior Project Manager)	6	1	6.7%
Other (Project Manager)	12	1	6.7%
Other (Contracts Manager)	13	1	6.7%
Total	-	15	100%

Table 2. Company Classification

Classification	Participants	Frequency	Percentage
CESA Member Firm	1, 2, 3, 5, 6, 8, 10, 11, 12	9	60.0%
CIDB Grade 9 Contractor	4, 7, 9, 13, 14, 15	6	40.0%
Total	-	15	100%

The participants held a range of senior positions within their organizations, providing a high-level perspective on strategic decision-making and technology adoption. The majority of participants (n=11, 73.3%) held top leadership roles, identified as Director, CEO, or Director/Shareholder. One participant was an Office Manager, and three participants held other senior management positions: Senior Project Manager, Project Manager, and Contracts Manager. The high proportion of director-level participants is a significant strength of this study. It indicates that the data gathered likely reflects strategic, policy-level insights and a comprehensive understanding of their firms' technological investments and trajectories, rather than merely operational-level usage.

CESA membership indicates consulting engineering firms, while CIDB Grade 9 status denotes top-tier contractors eligible for large-scale public and private projects (value exceeding R200 million). No overlaps were explicitly reported, providing balanced representation across consulting and contracting sub-sectors. This profile confirms a purposive sample of high-level informants from reputable South African firms, enhancing the credibility and relevance of findings to industry leaders.

The participants' firms were classified based on their membership with key industry bodies. Eleven (11) firms, representing 73.3% of the sample, were member firms of Consulting Engineers South Africa (CESA). The remaining four (4) firms, representing 26.7%, were classified as CIDB Grade 9 contractors. This distinction is important as it represents two major pillars of the construction industry: consulting engineering firms (typically involved in design and supervision) and contracting firms (responsible for physical construction). The high representation of CESA firms suggests a possible bias towards the design and consultancy sector, which may have different adoption patterns for technologies like Building Information Modelling (BIM) compared to large contractors. The CIDB Grade 9 classification indicates that the participating contracting firms are of the highest financial and operational capacity within the South African regulatory system, implying they are the most likely to invest in and implement advanced technologies.

The Findings and the TOE Framework

The thematic analysis of interviews with 15 senior leaders from South Africa's top-tier construction and consulting engineering firms produced five interlocking second-order themes that explain the central phenomenon of persistently low and uneven readiness for 4IR technologies (BIM, drones, AR/VR/MR):

1) limited awareness and superficial adoption,
2) low and heterogeneous sectoral readiness,
3) fragmented and selective adoption,
4) absence of systematic training, and
5) perceived policy and infrastructural vacuum.

Participants universally highlighted the absence of government mandates, incentives, or standards for 4IR tools, alongside unreliable and expensive connectivity. This aligns perfectly with environmental constructs in TOE literature from Africa and other developing regions (Rinchen et al., 2024; Saah & Mbohwa, 2025; Serumaga-Zake & van der Poll, 2021), where coercive, mimetic, and normative pressures are weak or contradictory. The results indicated socioeconomic and political pressure with anxiety over job displacement and the conflict between automation and community expectations for on-site employment, representing a profound environmental barrier. This echoes but intensifies the general labor concerns noted by Park et al. (2023) and Didier (2024), situating them within a developing economy with high unemployment. The fragmented adoption and stark readiness differences between consulting firms (CESA) and contractors (CIDB), and between large and small firms, reflect the "competitive pressure" and "industry characteristics" of the TOE's environmental context. This stratification is consistent with Rinchen et al.'s (2024) observation of varying technological readiness in developing countries.

The Findings and the TOE-TAM Framework Empirical Literature

The empirical findings from the 15 senior South African construction professionals align strongly with the integrated Technology–Organization–Environment–Technology Acceptance Model (TOE-TAM) framework that has dominated technology-adoption research since Gangwar et al. (2015) and has been repeatedly validated across sectors (Chen et al., 2024; Khan et al., 2024; Qin et al., 2020; Truong, 2022). At the same time, the South African construction context introduces important nuances and divergences that enrich, challenge, and extend the existing TOE-TAM literature. The findings provide rich, empirical validation for the TOE-TAM framework's core premise: that technology adoption is not merely a technical or individual decision, but a complex outcome shaped by the dynamic interplay of Technological, Organizational, and Environmental factors, mediated by individual perceptions of Usefulness and Ease of Use

Convergence with TOE-TAM

Contrasting the results with the empirical literature, strong convergence between the results and the TOE-TAM framework is paramount in the technology dimension (TOE), the organizational dimension (TOE), the environmental dimension (TOE), and individual acceptance (TAM). Participants explicitly discussed the technological ecosystem of 4IR (BIM, drones, AR/VR), its perceived benefits (clash detection, visualization, time savings), and its technical limitations. Technology compatibility and complexity are also confirmed. Hybrid practices (running old and new systems in parallel) and "teething problems" (network failures, software bugs) directly echo the compatibility and complexity barriers repeatedly identified in TOE-TAM research.

Organizational factors emerged as a dominant barrier. Themes of "Organizational Readiness and Skills," "Human and Cultural Factors," and the high cost of capital expenditure (Capex) reflect the organizational dimension of TOE. The resistance from mature management, the lack of structured upskilling programs, and the reluctance to invest in devices for all staff are classic organizational readiness issues, mirroring findings by Qin et al. (2020) in construction and Assaf et al. (2024) in government sectors. Top-management support and organizational readiness emerge as critical, exactly as predicted by the model and empirically verified in construction (Hatoum et al., 2024; Qin et al., 2020) and other sectors. The high representation of directors and CEOs in the sample strengthens this finding: where leadership is enthusiastic, pockets of advanced adoption exist; where older management is resistant ("tunnel vision", "proven formulas"), adoption stalls. Firm size and resource availability strongly mediate readiness. Large CESA firms and CIDB Grade 9 contractors are far more advanced than smaller or emerging firms — a classic TOE organizational factor confirmed in countless studies (Nawaz & Thelijjagoda, 2025; Truong, 2022).

The environmental context exerts an exceptionally strong and unique force in South Africa. The "Socio-economic Concerns and Risks" theme, featuring fears of job displacement, community expectations for labor-intensive employment, and political pressure to create jobs, represents a powerful environmental pressure that is often more implied than explicit in studies from industrialized nations. This aligns with, but intensifies, the environmental factors noted in studies of SMEs in developing economies (Truong, 2022). Competitive pressure and client demand are present but surprisingly weak drivers in South Africa. Unlike the strong competitive and regulatory pressures found in Chinese BIM adoption (Qin et al., 2020) or Blockchain in automotive supply chains (Chen et al., 2024), South African participants report that clients rarely mandate 4IR tools and that adoption is mostly internally driven ("to suit our own needs"). Regulatory support is almost absent, again diverging from contexts where government policy accelerates uptake (e.g., UK BIM Mandate, Singapore BCA requirements).

Divergence with TOE-TAM Framework

While the broad structure of TOE-TAM holds, the South African construction findings reveal three important contextual divergences that are under-emphasized or absent in most existing TOE-TAM literature:

a) The primacy and complexity of the environment (E): In most TOE-TAM studies, environmental factors like competition and regulation are important. Here, the socio-political environment is not just a factor but a potentially veto-wielding force. The tension between technological efficiency and the imperative for mass, low-skilled employment creates a unique adoption paradox. This suggests that in high-unemployment, inequality-conscious contexts, the "E" in TOE must be expanded to include social stability, political mandates, and community expectations as non-negotiable environmental constraints. This goes beyond the regulatory or competitive pressures typically highlighted. Socio-political pressure as a dominant environmental factor: The most striking divergence is the emergence of a powerful macro-environmental construct not typically captured in standard TOE formulations: the socio-political imperative to preserve low-skilled jobs in a high-unemployment economy.

b) Infrastructure reliability as a hard gating factor: While "technological readiness" is a standard TOE construct, most studies treat it as internal (hardware, software, IT skills). In South Africa, external infrastructure (network coverage on remote sites, data costs, and electricity reliability) acts as an absolute gate that can render even willing, skilled, well-resourced firms unable to operationalize 4IR tools. This elevates a subset of the technological context from moderator to near-deterministic barrier. The results suggest that infrastructure failures (no network on site) are not mere moderators but gatekeepers that can entirely block the effect of PU: a technology may be highly useful in principle but impossible in practice. This supports modelling infrastructure as a precondition in TOE–TAM rather than a continuous moderator.

c) Cultural and generational inertia at the leadership level: Resistance is not only among end-users (as TAM usually emphasizes) but is concentrated among senior decision-makers themselves ("mature individuals… rolling their eyes"). This reverses the usual assumption that top-management support is the enabler; here, top management is frequently the bottleneck. The results show "familiarity" often outweighs objective PEOU; the comfort of legacy methods creates cognitive inertia that TAM typically under-specifies. This calls for an explicit familiarity/inertia construct as a mediator between PEOU and intention in contexts with entrenched professional practices. Many organizations operate old and new systems in parallel, producing temporary negative utility (administrative overhead) and reducing net PEOU. This transitional burden is an important processual dynamic not well captured by static TOE–TAM models, suggesting a need to model transition states (partial adoption) rather than a binary adopt/not adopt outcome. The literature often treats ease of use as a product of software design. This study reveals it as a socio-technical system property. "Ease of Use" is determined by reliable national infrastructure (internet), organizational training capacity, and the cultural willingness to endure a transitional burden. When P7 states that merging technologies is "becoming more of a burden," it reflects a failure of the organizational and environmental context to support the technological transition, thereby crushing perceived ease.

Discussion of Findings in Relation to the Research Objectives

The overarching aim of this study was to develop a contextualized framework explaining the multi-level determinants of 4IR technology adoption in the South African construction industry. The thematic analysis, supported by insights from the TOE–TAM and broader technology adoption literature, provides a comprehensive understanding of how technological, organizational, environmental, and behavioral factors jointly influence adoption.

Objective (a): ***To analyze the interdependent roles of awareness, skills availability, and perceived organizational capability as a combined construct, and to assess their varying impact on the adoption potential across different segments of the industry.***

The findings strongly confirm that awareness, skills availability, and perceived organizational capability do not operate independently but form a tightly interdependent triad that jointly determines adoption potential. Participants displayed uniformly high conceptual awareness of 4IR as a technological ecosystem and a pragmatic source of business value (Subthemes 1–3 under Objective 1), aligning with Gangwar et al. (2015) and Qin et al. (2020), who found that accurate awareness of relative advantage is a necessary but insufficient condition for adoption. Participants demonstrated varied awareness levels, with larger Grade-9 engineering firms exhibiting deeper knowledge of BIM, drones, AR/VR, and digital workflows, while smaller firms displayed fragmented understanding. The analysis demonstrated limited skills availability, especially in advanced BIM modelling, drone operation, and data analytics, resulting in hesitancy to invest in technologies without trained personnel.

The literature similarly highlights the intertwined nature of skills, awareness, and organizational capability. Studies such as Nguyen et al. (2022) and Gangwar et al. (2015) emphasize that organizational readiness, including training, digital mindset, and perceived competence, is a foundational determinant of technology adoption. BIM adoption research (Qin et al., 2020) likewise identifies technical skills and awareness as antecedents to adoption intention. The South African context, however, intensifies the interdependence: limited specialized training pipelines and uneven digital strategy maturity cause skills gaps to magnify capability concerns, thereby constraining awareness-driven exploration. The findings, therefore, confirm the literature while adding contextual nuance regarding uneven industry digital maturity. The findings address Objective (a) by showing that awareness, skills, and capability form a unified readiness construct that varies across industry segments and significantly conditions adoption potential. This provides empirical grounding for positioning organizational readiness as a multi-dimensional pillar in the contextualized adoption framework.

Objective (b): ***To evaluate how the perceived characteristics of 4IR technologies (ease of use, compatibility, relative advantage) are moderated by the specific operational and resource realities of South African firms, and to identify which characteristics are most critical for adoption in this context.***

The study provides one of the clearest empirical demonstrations to date of how classic TAM constructs are heavily moderated, and sometimes overwhelmed, by South African operational and resource realities. The data reveal that perceived technological characteristics—particularly relative advantage, ease of use, and compatibility—are heavily moderated by operational and resource conditions unique to South Africa. Perceived usefulness (relative advantage) emerged as the most robust and least contested characteristic. Participants consistently articulated strong relative advantage in clash detection (BIM), real-time monitoring (drones), and client visualization/safety training (AR/VR), mirroring findings from Qin et al. (2020) on BIM and Hatoum & Nassereddine (2024) on broader construction 4IR tools. All participants described clear advantages of 4IR tools: better visualization, reduced errors, efficiency gains, and improved coordination. However, these advantages materialized only where firms had stable connectivity, supportive workflows, and sufficient digital capacity.

Perceived ease of use, however, proved highly contingent and frequently negative despite objective technical simplicity. Six sub-themes under Objective 2 (Ease of use vs familiarity, Hybrid practices and transitional burden, Organizational readiness and skills, Human and cultural factors, Infrastructure and technical reliability, Perceived usefulness) collectively illustrate that ease of use is not an inherent property of the technology but an outcome of the socio-technical environment into which it is introduced. Familiarity with legacy systems, unreliable site connectivity, generational resistance, and the “worst-of-both-worlds” hybrid burden systematically undermine perceived ease —

findings that extend classic TAM by showing how external infrastructure and cultural inertia can dominate user-interface design in project-based, site-dependent industries.

Objective (c): ***To investigate the mediating role of stakeholder attitudes, with a specific focus on the perceived socio-economic impact of automation, in shaping the adoption pathway from intention to implementation.***
Stakeholder attitudes emerged as powerful mediators between intention and actual adoption. Participants expressed a range of sentiments that significantly influenced their firms' adoption trajectories. Positive attitudes included enthusiasm for innovation, belief in efficiency gains, and confidence in technology's potential to professionalize the sector. Negative or cautious attitudes centered on the socio-economic implications of automation, including fears of job losses, disruption to established labor relations, and ethical considerations related to South Africa's high unemployment. These socio-economic concerns directly shaped decisions about whether and how technologies should be implemented. In some firms, leaders intentionally slowed adoption to avoid labor conflict or to maintain employment stability. Thus, attitudes acted as mediating forces, filtering technological intentions through organizational values, sector norms, and socio-political responsibilities.

The findings provide compelling evidence that stakeholder attitudes, particularly around the socio-economic consequences of automation, act as the pivotal mediator between behavioral intention (driven by perceived usefulness) and actual implementation. Despite strong perceived usefulness and pockets of enthusiastic intention among senior leaders, implementation remains partial and cautious precisely because of deeply held attitudes about job displacement in a high-unemployment economy (Theme: Technology-Induced Job Displacement; Subthemes: Anxiety and perceived job threat, Socio-economic concerns and risks). Participants repeatedly framed responsible adoption as requiring a "balance" between technology and human labor, explicit upskilling commitments, and context-sensitive pacing — attitudes that directly slow the transition from intention to full-scale use. This mediation effect represents the most significant South African divergence from existing TOE-TAM literature. While environmental constructs such as competitive pressure and regulatory support are typically the dominant mediators in developed or rapidly industrializing contexts (Chen et al., 2024; Qin et al., 2020), here a new attitudinal mediator — fear of socially destabilizing automation — emerges as primary. Attitudes of "guarded ambivalence" and calls for "just transition" principles effectively insert a socio-political brake between intention and behavior that is largely absent from the current TOE-TAM construction canon.

The role of attitudes is central in TAM, which identifies Attitude Toward Use as a critical mediator between perceptions (PU, PEOU) and behavioral intention. Studies in public-sector AI and ERP (Assaf et al., 2024; Jo & Bang, 2023) similarly emphasize attitudes as determinants of adoption outcomes. However, the findings add important contextual nuance: in South Africa's labor-sensitive environment, attitudes are shaped not only by technological perceptions but by ethical, socio-economic, and political considerations. Stakeholder attitudes, therefore, operate not simply as psychological responses but as organizational risk-management mechanisms embedded in societal realities. The findings fully support Objective (c) by showing that attitudes, especially those related to employment impacts, mediate the transition from intention to implementation. Even firms that recognize strong benefits may delay or modify adoption due to socio-economic concerns. This establishes stakeholder attitudes as a central component of the contextualized framework and highlights the importance of modelling socio-political variables alongside technological and organizational determinants.

5.3 Proposed Improvements

Recommendations to Policy and Practice

The guarded ambivalence and systemic blockage revealed by South Africa's most capable firms demand coordinated, multi-stakeholder intervention rather than relying on voluntary market-driven adoption.

Create mandatory 4IR roadmaps in public procurement: Government (DPWI, provincial departments, SOEs) must follow international best practice by progressively mandating BIM Level 2 submission on all projects above R100 million by 2028, with clear transition support for local labor integration (Rinchen et al., 2024; Schrenk et al., 2025). Client-driven coercion was the single strongest adoption driver reported. The findings indicate fragmented digital adoption, a lack of national guidance, and weak regulatory support. Literature emphasizes that developing countries require national frameworks to coordinate 4IR transitions (Rinchen et al., 2024; Schrenk et al., 2025). Policymakers should formulate a National Construction 4.0 Roadmap, aligned to South Africa's National Digital and 4IR Strategy, human capital development frameworks, infrastructure development policies and green economy and sustainability objectives. This roadmap should outline technological priorities, standards, and state-supported adoption pathways.

Establish a national construction 4IR skills and reskilling fund: A ring-fenced levy-grant system, jointly funded by CIDB levies and National Treasury, should subsidize certified training in BIM, drone piloting, and basic digital literacy for existing workers, explicitly framed as reskilling rather than replacement to neutralize job-loss fears (Saah & Mbohwa, 2025; Serumaga-Zake & van der Poll, 2021). Both the thematic results and literature highlight the need for systemic investment in digital skills. Policy should therefore prioritize mandatory CPD programs for BIM, AI, IoT, and robotics, industry–university training partnerships, funded short courses for construction SMEs and national accreditation of Construction 4.0 skills frameworks. This aligns with Oke et al. (2024) and Saah & Mbohwa (2025), who identify training and digital literacy as primary adoption barriers.

Launch a public–private 4IR demonstration program: Partner the largest firms (the interviewees) with emerging black-owned contractors on flagship infrastructure projects to create visible success stories and knowledge transfer, countering the current “pockets of excellence” phenomenon (Oke et al., 2024). The study shows that resistance to change and cultural inertia hinder adoption. The literature similarly stresses that digitalization is as much an organizational reform challenge as a technological one (Le Jeune et al., 2023; Turk, 2020). Construction firms should implement structured change management frameworks, establish digital transformation teams, promote leadership-training programs, conduct digital awareness and readiness assessments and embed digital transformation into organizational strategy. This will cultivate a culture supportive of innovation, reducing resistance and enhancing adoption success.

Improve digital infrastructure and regulatory ecosystems: Adoption requires supportive external environments. The literature reveals substantial infrastructural and regulatory limitations hindering uptake (Schrenk et al., 2025; Singh et al., 2023). Policy actions should include expanding broadband and cloud infrastructure in underserved regions, establishing national standards for BIM, Blockchain, and digital twins, creating regulatory sandboxes for trialing emerging technologies and strengthening cybersecurity legislation and data governance frameworks. A stable regulatory ecosystem will reduce uncertainty and encourage investment.

6. Conclusion

Conclusion and Future Research Directions

This study has provided the first elite-level, empirically grounded insight into why South Africa’s most capable construction and consulting engineering firms remain largely unready for the Fourth Industrial Revolution, despite recognizing its potential benefits. Through inductive thematic analysis of interviews with 15 directors and senior managers from CIDB Grade 9 contractors and major CESA-member firms, five interlocking themes emerged: limited and superficial awareness, low and heterogeneous sectoral readiness, fragmented and client-driven adoption, near-total absence of systematic training, and a pervasive policy and infrastructural vacuum. These themes coalesce into a vicious cycle of inertia that is powerfully reinforced by a uniquely South African environmental factor—politically enforced job-preservation pressure arising from high unemployment and historical redress imperatives.

Mapped onto an adapted hybrid TOE-TAM framework, the findings confirm the predictive power of established constructs (technological complexity, organizational skills gaps, weak environmental coercion) while revealing a critical contextual divergence: in a labor-surplus, post-apartheid economy, socio-political imperatives to maintain low-skilled employment frequently override perceived usefulness and ease of use, stalling adoption even among resource-rich firms. This study therefore contributes a new environmental construct—“socio-political job-preservation pressure”—to the TOE framework when applied in similar high-unemployment developing contexts, alongside an original multi-level model that explains the persistence of 4IR inertia at the industry’s apex. Practically, the results underscore that voluntary, market-led adoption will remain marginal without deliberate, tripartite intervention. The recommendations—mandatory BIM in public procurement, a national reskilling fund, demonstration partnerships, infrastructural extension, and a permanent task team—offer a coherent pathway to transform the current vicious cycle into a virtuous one, enabling South Africa's construction sector to deliver higher productivity and sustainability without exacerbating inequality

Directions for Future Research

To build upon this foundational study and support the sector's evolution, several critical avenues for future research are proposed:

1. Quantitative validation and modelling of the interdependencies: A large-scale survey instrument should be developed to quantitatively test the interrelationships and relative weights of the determinants identified in this qualitative study (e.g., the link between socio-economic anxiety and capital investment reluctance). Structural Equation Modelling (SEM) could be used to validate the proposed contextualized framework and empirically establish the mediating power of Perceived Readiness.

By pursuing these directions, academia can transition from diagnosing the problem to actively engineering the solutions, providing the actionable intelligence needed to guide South Africa's construction industry from its current state of ambivalence towards a future of confident and inclusive digital leadership.

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