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Appraising the Role of Technology as a Primary Driver of Digital Transformation in Construction 4.0 Adoption Using a Qualitative Approach

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Abstract

The advancement of technology has improved the supply chain of major sectors of the economy, including construction. Thus, digital technology may advance the transition from the conventional practices to the Construction 4.0 environment, particularly in developing countries. Studies are scarce concerning the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector. Thus, this study appraises digital technologies for construction project execution and sheds light on the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector. The study utilised a qualitative approach and included face-to-face semi-structured interviews with 50 participants in South Africa who are knowledgeable in Construction 4.0 and digital technology. The researchers also adopted thematic analysis using Atlas.ti and NVivo to analyse the data. The findings reveal that the benefits of digital technologies for construction project execution in the South African construction sector, and, by extension, for transforming conventional practices into Construction 4.0, cannot be overstated if well embraced and implemented. Findings also identified the key technologies driving digital transformation in Construction 4.0 Adoption in the South African construction sector, grouping them into six sub-themes. This study contributes to the theoretical discourse on technology as a primary driver of digital transformation in the context of Construction 4.0 adoption. It also offers practical insights into project resilience and the role of adopting digital technologies in the construction industry, particularly in the South African construction industry context.

Keywords: Construction 4.0; digital drivers; South Africa; qualitative research; technology; transformation

1. Introduction

The digitisation period has had a significant impact on the transition of major industries by integrating digital technologies, automation, cyber-physical systems, and data-driven decision-making, especially in the production industry [1]. Digital technologies, such as Artificial Intelligence (AI), big data analytics, 3D Printing (3DP), the Internet of Things (IoT), Modular Integrated Construction (MIC), smart automation, and cloud computing, are integrated, enabling intelligent process optimisation, interoperability, and real-time connectivity [2,3]. Researchers opined that in the construction industry, technological integration is known as Construction 4.0 [4]. It is a paradigm that applies Industry 4.0 principles to construction tasks across the whole project lifecycle. Industry 4.0 concepts can be implemented in the construction sector by institutionalising digital workflows, developing skills, and reforming policies to promote innovation [5]. Construction 4.0 entails integrating digital technologies such as Building Information Modelling (BIM), IoT, AI, robots, automation, big data analytics, and cyber-physical systems across the construction project lifecycle [4]. They are part of the Fourth Industrial Revolution (4IR) technology [5]. Advanced economies such as Singapore and the United Kingdom have made significant progress in digitising their building sectors. It has increased predictability in construction projects, decreased cost overruns, and improved collaboration among key stakeholders [5]. The advantages of Construction 4.0 may entice emerging countries' construction industries, including South Africa's [6]. The inadequate understanding of technology's role as a key driver of digital transformation in Construction 4.0 Adoption, particularly in developing countries' construction sectors, may have influenced implementation. Many third-world countries are not encouraging their citizens to adopt digital technology [6].

A digital environment can transform the construction sector, increasing productivity and contributing to GDP growth in developing countries like South Africa [7]. Adopting the Construction 4.0 framework, which evolved from Industry 4.0, might help the construction sector move toward more efficient production, business models, and value chains throughout project life cycles [8]. Thus, research on the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector is limited concentrated on supplying sustainable housing through digital technologies such as 3D Printing, laser scanning technology (LST), drones, and others [3,4]. The South African construction industry has been inconsistent in its embrace of digital technologies [2]. South African construction enterprises have challenges in implementing innovative technologies[6]. Despite Construction 4.0's growing responsiveness, Oke et al. (2018) were the only ones to mention barriers; others failed to provide in-depth insight or clarity on how stakeholders would mitigate the various challenges to improve the key driver of technology integration and achieve a Construction 4.0 environment. This has created a substantial gap, underscoring the need for empirical research into the role of technology as a key driver of digital transformation in the South African construction sector.

The use of advanced digital technology to ease the construction sector's shift from a traditional approach to a Construction 4.0 environment in many developing countries has become increasingly relevant. This is because of the benefits, such as mitigating project delays and poor time management, particularly in third-world countries [8]. The implementation of advanced digital technologies across the construction project life cycle affects project outcomes, innovation, performance, and excellence [9,10]. Studies are scarce concerning the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector. Thus, this study appraises digital technologies for construction project execution and sheds light on the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector through the following objectives:

i. To identify digital technologies for the execution of construction projects in the South African construction sector.
ii. To investigate the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector.

2. Literature Review

The construction industry is coping with increasingly sophisticated and futuristic designs, a wide range of materials, green structures, smart homes, and other efforts [5]. Given the rapid technological growth of 4IR, the building sector should replace traditional techniques with digital and contemporary technologies. The importance of the construction sector's quick transition from conventional construction to Construction 4.0 cannot be overstated [7–9]. Construction 4.0 is a subset of Industry 4.0, primarily designed for the architecture, engineering, and construction industries [7,9]. Construction 4.0 comprises transdisciplinary digital technologies, techniques, and concepts that enable digitalisation and automation across the construction process [8]. It integrates a range of advanced digital and physical technologies, including BIM, IoT, robotics, artificial intelligence, and

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off-site manufacturing [7]. Thus, Construction 4.0 entails not just integrating digital technology on-site, but also holistically integrating technologies and innovative practices throughout the full construction project lifecycle. These technologies improve stakeholder communication and collaboration, increasing efficiency and production in building projects. Figure 1 depicts a three-transformational trend model. BIM and a Cloud-based Common Data Environment (CDE) form the foundation of the Construction 4.0 framework, which is supported by major digitisation technologies, including AI, cloud-based project management, AR/VR, IoT, robots, sensors, cybersecurity, and blockchain [7]. Throughout the building project life cycle, users of technologies such as wearable sensors, automated machinery, and additive manufacturing systems collect and process real-time data using digital feedback loops. The transmission of data between the site and the cloud enables predictive analytics, proactive maintenance, and adaptive management of on-site activities, demonstrating Construction 4.0's potential to increase output and reduce risk in the industry. The model is effective in most advanced countries [10]. Understanding the role of these digital technologies as key drivers of digital transformation in Construction 4.0 Adoption in developing countries, including the South African construction sector, is pertinent in the era of construction digitisation.

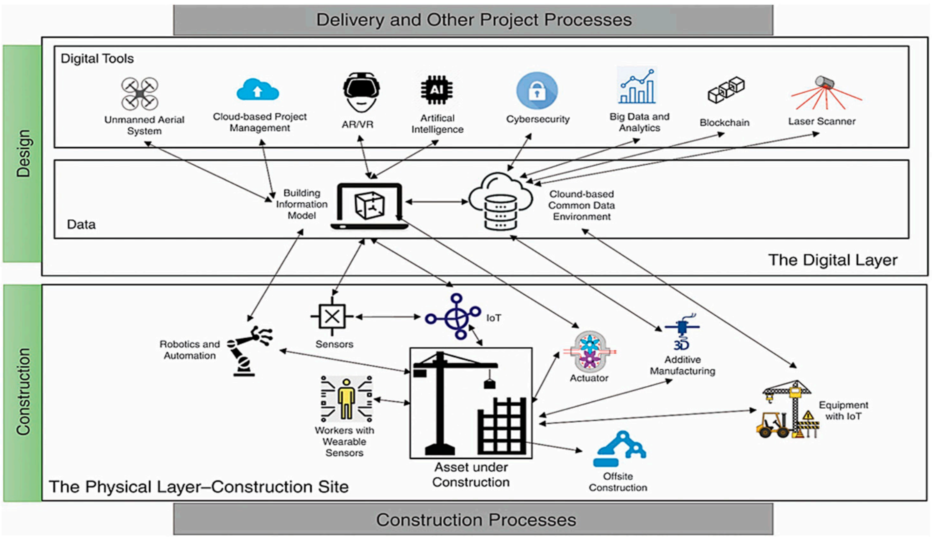

Figure 1. Construction 4.0 Model[7].

To position the industry to meet contemporary demands for efficiency and environmental responsibility, the shift from conventional construction to Construction 4.0 promises to address long-standing inefficiencies, improve project outcomes, and promote sustainability [2] Dhamak et al., 2025). By addressing long-standing inefficiencies, improving project outcomes, and fostering sustainability, these technologies position the industry to meet contemporary demands for environmental responsibility and efficiency. The integration of cutting-edge digital technologies like IoT, BIM, autonomous machinery, AI, AR/VR, and predictive analytics is one of the reasons for this [9]. One of the main advantages of Construction 4.0 is sustainability, as digital technology enables accurate monitoring and management of environmental impacts [10]. The advantages are outlined in Table 1, which is drawn from Casini (2021). Practitioners should promote a culture of digital collaboration and encourage adoption through workplace rules and leadership, especially in underdeveloped nations where innovation is frequently constrained [11–13].

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Table 1. Digital technologies' advantages in facilitating Construction 4.0 [14].

Advantages	Enablers
Industry performance maximisation	1. Using a lifecycle approach
	2. Cutting waste and inefficiency
	3. Integration that is longitudinal, vertical, and horizontal
	4. Better time and cost performance
	5. Considerably enhanced safety performance
	6. Improved quality
	7. A better perception of the sector
	8. Enhancing the construction project's quality
	9. Improving amicable connections with other experts
	10. Ensuring proper planning, supervision, and management of construction
	11. Promoting smooth communication during the project
	12. It promotes staff involvement in decision-making
	13. Improving customer contentment
	14. Enhancing professional communication in the construction industry
	15. Timely and cost-effective delivery
	16, A better rapport with customers
	17. Enhance the method of production and distribution
	18. Lean management techniques are promoted
	19. Recognising new construction risks, such as supply chain, performance, and safety
	20. Dynamic knowledge of construction operations' performance and overall site conditions

3. The Study's Theoretical Framework

Innovative technologies are advancing rapidly across all fields, including construction. Construction processes can be improved and integrated with digital technology [15,16]. Common models for digital innovation include the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT). However, UTAUT 3, a variation of UTAUT, was used for this investigation. The model provides a thorough and flexible framework for determining the factors influencing user adoption or resistance to digital technology [17]. TAM models may not be appropriate for the construction industry because of the complexity of different stakeholders, and they assume that operators view ease of practice and the value of the expertise as the fundamental factors influencing their decision to either reject or accept the technology [18]. Because UTAUT 3 provides a more thorough examination of technology adoption than TAM, it is more appropriate for building 4.0.

Additionally, it incorporates organisational preparedness, human factors, and technological circumstances that facilitate the adoption of Construction 4.0. Construction stakeholders to share the advantages of the digital technology system [16]. Currently lacking, this could contribute to the realisation of Construction 4.0. Achieving the intended goal requires the industry's major players to embrace and adopt technology advancements. Using cutting-edge digital technologies offers several advantages. This covers project sustainability, safety precautions, and productivity results [19]. The idea behind incorporating important digital drivers into the implementation of Construction 4.0 in the South African construction industry is to offer several benefits. This includes lower construction costs, improved safety, greater project efficiency, and better project management from pre-contract to post-contract administration. This is because digital technology-driven tools can optimise resource allocation, automate operations, and provide real-time insights, resulting in cost and time savings without sacrificing the quality of construction projects. When applied by the right parties, stakeholders can incorporate digital technologies and add value to building products, goods, and services [20]. Construction team members' resistance to change may pose obstacles to stakeholders seeking to adopt and use these digital technologies.

4. Research Method

The researchers employed a qualitative approach. It is the second phase of a larger study, and the approach used is consistent with that of [21],who investigated the incentives of digital technology users in the industry using the same research design. The researchers used five case studies and semi-structured interview questions to support Yin's (2018) claim that contextual understanding and data richness should take precedence over sample size in multiple case designs. The five chosen projects, which are spread across various parts of South Africa, are as follows: Project 1 (a student residence building in Gauteng) was delayed by ten months; Project 2 (a multi-story housing complex in the Western Cape) was delayed by eight months; Project 3 (a residential block on a university campus in KwaZulu-Natal) was delayed by twelve months; Project 4 (a refurbishment of student housing in the Free State) was delayed by nine months; and Project 5 (Eastern Cape, new student residence delayed by eleven months). To choose appropriate interview subjects, the study used purposive and snowball sampling strategies. For the snowball sample, the study began by contacting a few willing volunteers under the guidance of the principal author. These specialists then directed the researcher to other experts in Construction 4.0 and digital technology. Ten experts were interviewed for each case study, and the study attained saturation at the 48th interviewee out of 50. The information about the participants is shown in Table 2. The researchers included four South African provinces in the study. This comprises Limpopo, Gauteng, KwaZulu-Natal (KZN), and the Free State. In-person interviews allow for deeper discussion of complex subjects through verbal and nonverbal cues; all interviews were conducted in person and in English [22,23]. This includes facial expressions, tone, and body language. This is the elegance of collecting data in person.

Table 2. Participants' background.

Participant	**Rank/Firm**	**Years of Experience and Academic Qualifications**	**Geopolitical Zone/Location and Participant Code (Five Case Studies)**					**Total**
			Case 1	**2**	**3**	**4**	**5**	
Client Representative	Clint Representative	Not below 10 years and	CR1	-	-	CR2	CR3	**3**

Construction Project Manager	Consultant	a Bachelor's degree, respectively	CPM1	CPM 2	CPM 3	CPM4	CPM5	**5**
Quantity Surveyor			QS1	-	QS2	QS3	QS4-QS6	**6**
Architect			Arch1	-	Arch 2	Arch3	Arch4	**4**
Civil Engineer			CE1	CE2-CE3	CE4	CE5	CE6	**6**
Structural Engineer			SE1	SE2	SE3	SE4-SE5	SE6	**6**
Electrical Engineer			EE1	EE2	EE3	EE4	-	**4**
Mechanical Engineers			ME1	ME2	ME3	ME4	ME5	**5**
Construction Health and Safety Agent			CHSA 1	CHS A2	CHS A3	CHSA 4	CHSA 5	**5**
Construction Manager	Contractor		CM1	CM2	CM3	-	-	**3**
ICT Infrastructure	Consultant		-	ICT1	-	-	-	**1**
Development Manager			-	DM1	DM2	-	-	**2**
Cumulative per case study			**10**	**10**	**10**	**10**	**10**	**50**
Total								

Source: Authors' work.

The interviewees were provided with consent forms and informed of the study's purpose. This meets the ethical standards. This investigation was conducted and verbatim transcribed. The duration of each interview was between forty-five and sixty minutes. The generated codes were reorganised according to occurrence, reference, and frequency. The categories gave rise to themes, each with a different goal. To evaluate and improve the interview methodology, the study also conducted a pilot study with five participants. The interview questions were slightly altered. For this study, the main interview questions were:

Q1. How satisfied are you with the industry's current adoption of digital technology?

Q2. Can you identify digital tools essential to consultants and contractors for successful construction project delivery?

Q3. Can you identify digital tools that can enhance design coordination, class detection, and accurate planning?

Q4. How can digital tools increase efficiency in their operations, specifically during construction?

Q5. In your opinion, what are the ideal physical digital technologies to assist in minimising construction delays?

Q6. What is the impact of using digital technology, such as MIC or 3DP, as key driver technology on projects during construction?

Q7. Can BIM pair with other digital tools?

Q8. What are the tools that can be utilised in the digital layer?

Q9. What are the most suitable ideal digital tools to be utilised in the "physical" layer of the cyber-physical ecosystem?

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The researchers employed a thematic analysis of the data they collected. Theme analysis is used to find patterns of interrelatedness and opinions surrounding the topic under research, leading to a deeper understanding [23,24]. The researchers analysed the data they had collected using Atlas.ai and NVivo, a qualitative analysis program created to enhance the rigour and depth of data interpretation through the six steps described by [25]. To engage with the data, the researchers first read the 50 transcripts. Open coding and keyword research came next [26]. Third, the researchers used axial coding to create subcategories from the previously formed open sub-themes. Selective coding, which identified and verified the most important text from the 50 transcripts, was the next stage [27]. Key participants were then called by the study to verify the developing principal results and to compare the themes they had created with what they had heard during the interviews. Ultimately, the study concluded that understanding the role of emerging digital technologies is key to the adoption of Construction 4.0 in the South African construction sector.

5. Findings

5.1 Theme One: Digital Technologies for the Construction Project Implementation

Theme One assessed practitioners' use of digital technologies across the planning, design, construction, and maintenance stages of construction project implementation to improve project delivery. The theme is clustered into four sub-themes.

5.1.1. Digital Tools Essential to Construction Consultants and Contractors

The findings highlight a broad ecosystem of smart construction, mechanical, and electrical technologies essential for improving current project delivery in the South African construction sector (majority). They also emphasise the importance of digital planning and coordination platforms, noting that these tools are vital for enhancing accuracy, reducing delays, and supporting data-driven project decision-making (majority). Participant CPM1 states, "…. *for projects to run smoothly, tools like BIM, MS Project, and proper project-planning software are non-negotiable … they help everyone speak the same language….*" In the view of Arch3, who reinforced CPM1, says "… *Cloud computing and communication tools allow teams to share updates instantly, which cuts down the time lost through traditional paperwork and miscommunication…*" The findings identify BIM, MS Project, IoT, sensors, drones, AI, cloud computing, communication tools, and project planning software as key digital tools crucial to construction consultants and contractors. These technologies form the backbone of the modern construction industry, which increasingly embraces automation. Participant CPM5 states, "…. *3D printing, drones, and digital twins are game changers… they speed up work and provide real-time visibility of what's happening on site…*" Participant CHSA4 adds, "… *RFIDs and big data analytics help track resources and predict project risks, which avoids unnecessary delays…*" The findings also reveal that digital tools such as 3D Printing, digital twins, drones, RFIDs, big data analytics, and artificial intelligence are essential for improving monitoring, optimising resources, and reducing errors. The study further shows that, alongside innovative digital tools, recognising the significance of traditional physical construction tools, including surveying equipment, bricklaying tools, underground service detectors, measuring instruments, and scaffolding, is equally important. Participant EE4 states, "….. *Digital tools alone won't improve delivery; basic site equipment like detectors, scaffolding, and proper measuring tools are still essential….*" The findings highlight a broad ecosystem of smart construction, mechanical, and electrical technologies essential for improving current project delivery in the South African construction sector (majority). They also emphasise the importance of digital planning and coordination platforms, noting that these tools are vital for enhancing accuracy, reducing delays, and supporting data-driven project decision-making (majority). The findings identify BIM, MS Project, cloud computing, communication tools, and project planning software as key digital tools crucial to construction consultants and contractors. These technologies form the backbone of the modern construction industry, which increasingly embraces automation. Participant CPM5 states, "…. *3D printing, drones, and digital twins are game changers… they speed up work and provide real-time visibility of* *what's happening on site…*" Participant CHSA4 adds, "… *RFIDs and big data analytics help track resources and predict project risks, which avoids unnecessary delays…*" The findings also reveal that digital tools such as 3D Printing, digital twins, drones, RFIDs, big data analytics, and artificial intelligence are essential for improving monitoring, optimising resources, and reducing errors. The study further shows that, alongside innovative digital tools, recognising the significance of traditional physical construction tools, including surveying equipment, bricklaying tools, underground service detectors, measuring instruments, and scaffolding, is equally important. Participant EE4 states, "….. *Digital tools alone won't improve delivery; basic site equipment like detectors, scaffolding, and proper measuring tools are still essential to avoid mistakes and rework…*"

5.1.2. Tools for Design Coordination, Clash Detection, and Accurate Planning

The findings identify AutoCAD, Revit, BIM, and Autodesk suites as the essential digital tools to enhance design coordination, class detection, and accurate planning (majority). These tools are foundational and cut across construction practitioners' disciplines. The benefits of these tools include integrating drawings, enhancing visualisation, and reducing inconsistencies among professionals. Participant ICT1 says, "… *If we are talking about proper coordination, you can't avoid tools like Revit and BIM… they help the whole team visualise the same model and detect problems early…*" SE2 corroborates ICT1 submission, and says "… *AutoCAD and Autodesk give us structured design outputs, but BIM takes it to another level by integrating all the services into one model….*" For clash detection, including scanning machines, findings indicate that BIM is an effective tool. Participant ME4 says, "…. *Clash detection tools save us time. If we catch clashes early, we avoid redesigns later, which is where most delays come from….*" Participant CE4 says, "… *Laser scanning and underground service detectors give us accurate site information… guesswork is what slows projects down…*" Findings also reveal that combining digital clash-detection tools with physical detection equipment significantly improves accuracy. The planning accuracy improves significantly when scheduling software integrates with AI-based forecasting, digital twins, and cloud-based information systems (majority).

5.1.3. Use of Digital Tools to Increase Efficiency

The findings reveal that adopting digital tools in construction projects can enhance project productivity and efficiency (majority). On the other hand, Participants CR2 and CHSA4 opine that they do not consider digital tools in their construction projects to improve productivity.

5.1.4. Utilisation of Digital Technologies Across Project Stages

The findings indicate a positive response to the adoption of digital technology on construction projects (majority). This includes across all stages. However, the findings reveal that the use of digital technologies on construction projects is not encouraging. This calls for concern. This suggests that although there is greater acceptance of digital technology, there remains an implementation gap among construction professionals, which can be attributed to several factors beyond the scope of this paper.

5.2. Theme Two: Technology to Be a Key Driver of Digital Transformation

Theme Two investigated the role of technology as a key driver of digital transformation in Construction 4.0 Adoption in the South African construction sector. This theme is clustered into six sub-themes.

5.2.1. Key Driver Technology During Construction

First, findings identified the key driver technology during construction. This includes BIM, Modular Integrated Construction (MIC), 3D Printing (3DP), sensors, drones, laser scanning, and immersive technologies. Findings further reveal that BIM plays a critical role as the central enabling technology for Construction 4.0 (majority). BIM is the integrating digital backbone that enables coordination, data exchange, and interoperability among diverse technologies across the project lifecycle. Findings indicate that BIM is the platform through which information from physical technologies such as sensors, drones, and laser scanning is consolidated, visualised, and translated into actionable decisions (majority). Second, findings indicate that other technologies, such as MIC and 3DP, serve as delivery and production innovations, with effectiveness significantly enhanced when embedded in a BIM-enabled environment. For example, MIC relies on early design coordination, standardisation, and accurate digital models. 3DP depends on precise digital inputs for automation and material optimisation. Similarly, sensing technologies and drones serve as data-acquisition tools, capturing real-time or as-built information that feeds into BIM models to support monitoring, control, and performance evaluation. Without BIM, these technologies were perceived as fragmented or operating in isolation, limiting their transformative potential. Findings suggest that strengthening BIM adoption is a prerequisite for scalable Construction 4.0 implementation in South Africa. This is because BIM is a key driver technology for Construction 4.0, a designation that is theoretically justified by its unique capacity to integrate, coordinate, and mediate interactions across the digital and physical layers of construction systems. From a Construction 4.0 perspective, Participant ICT1 says, "…. *BIM occupies the core of the digital layer while directly interfacing with physical-layer technologies, thereby enabling system-level coordination, feedback loops, and scalability...*"

5.2.2. Ideal Physical Digital Technology to Minimise Delays

The findings reveal management tools, system tools, technology tools, AR/VR, BIM, drones, laser scanning, sensors, automation, forecasting systems, smart sheets, site sensors, centralised data repositories, weather forecasting software, RFI management tools, the 3D printers, project management systems, cloud-based data systems, automation, risk assessment tools, health and safety tools, brick measurement instruments, and prefabrication systems as the ideal physical digital technologies to prevent or mitigate construction delays (majority). These digital technologies can help minimise construction delays and enable Construction 4.0 (majority).

5.2.3. Impact on Projects in Using MIC or 3DP

The findings reveal that among the most frequent digital technologies, such as MIC or 3DP, their usage can improve construction project performance, including construction quality, time collaboration, material optimisation, efficiency, and cost (majority). The study also shows that adopting technologies shortens construction cycles, improves teamwork, and increases precision in material utilisation. As part of the key drivers of digital transformation in Construction 4.0 adoption, findings identify that accuracy, quality, communication, and tracking are key components of the role to enhance the achievement of Construction 4.0.

5.2.4. Ability of BIM to Pair with Other Digital Tools

The findings reveal that BIM can be paired with all other digital tools used during physical construction (the majority). It makes BIM a key driver of technology for Construction 4.0.

5.2.5. Tools to Be Utilised in the "Digital" Layer

The findings reveal that digital twins, BIM, cloud computing, generative artificial intelligence, big data analytics, blockchain, cloud-based data storage, and three-factor authentication are tools that can be utilised in the digital layer (majority). These tools are crucial for enabling a Construction 4.0 environment, along with data storage and management to improve construction project outcomes (QS2, Arch1, and CM3). Participant Arch2 says, "…. *BIM is the backbone of digital construction; it links everything together, …. digital twins bring projects to life by allowing us to simulate and predict performance before physical work begins…..*" Participant QS2 says, "… *without cloud systems, collaboration across sites would be almost impossible…*"

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5.2.6. Digital Tools to Be Utilised in the "Physical" Layer

The findings reveal that prefabrication systems, 3D Printing, robotics and automation, smart construction sites, and AR and VR are the most suitable digital tools to be utilised in the "physical" layer of the cyber-physical ecosystem (majority). Prefabrication systems and 3D Printing are increasingly common because they are seen as enablers of effective, precise, and accelerated on-site and off-site construction activities that directly support a Construction 4.0 environment (ICT1). Others also featured strongly, reflecting a focus on advanced technologies that directly interact with the physical construction environment to improve safety, accuracy, and, most importantly, productivity. This is the core motivation for this study. Participant ICT1 says, "… *BIM is the entry point for digitalisation, and digital twins take it further by helping us predict how the system will behave*…." Findings also show that the tools enhance analytical capability, transparency, and automation across project phases (majority). Participant QS4 says, "… *AI and big data help us identify patterns we cannot pick up manually*," while another (QS3) added that blockchain "*gives us trust in digital records and transactions*…"

6. Discussion of Findings

Findings reveal how construction practitioners interpret, value, and implement digital technologies across the planning, design, and construction stages, including descriptions of digital tools, their significance, purpose, and depth of application in construction. It shows that although digital tools, such as BIM, MS Project, IoT, sensors, drones, AI, cloud computing, communication tools, and project planning software are seen as vital to modern project delivery, which support [3] and [28], their application remains selective, tool-focused, and driven by specific functions rather than systemic or transformative change. This indicates that digitalisation in the South African construction sector is advancing gradually, with practitioners mainly adopting technologies to tackle immediate coordination and efficiency issues rather than achieving the full Construction 4.0 vision. The dominance of platforms like BIM, AutoCAD, Revit, Microsoft Project, and cloud collaboration tools shows a strong preference for technologies that are highly observable and offer immediate performance benefits, especially in design coordination, clash detection, and scheduling accuracy. This trend aligns with earlier research that found that construction professionals favour digital tools that deliver quick, tangible productivity gains over more abstract or systemic innovations [29–31]. Findings highlight a distinct separation made by practitioners between digital coordination tools and physical construction technologies. Findings also recognised the value of advanced physical tools, such as surveying equipment, detection devices, and automated machinery. They were mostly seen as extensions of traditional practices rather than as parts of an integrated cyber–physical system. This limited integration aligns with observations, who found that while construction professionals are willing to work with digital technologies, their use tends to be isolated and not fully integrated into broader Construction 4.0 frameworks [12,32]. Construction practitioners often stick to familiar tools, such as Microsoft Project and basic BIM features, though they recognise the potential of more advanced digital solutions. This contradiction supports the findings that found that while industry discussions about advanced digital technologies are increasing, their adoption is limited by skills shortages, interoperability issues, and fragmented workflows [33,34]. However, BIM is consistently regarded as essential for identifying clashes and reducing RFIs; findings also noted that design conflicts are still often found during construction. This indicates that BIM is frequently used mainly as a visualisation tool rather than as a comprehensive decision-support and coordination system integrated across all project teams. Such limited application challenges the optimistic view in the literature that BIM adoption automatically improves project outcomes.

The findings identify a wide range of digital tools, including BIM, MIC, 3D Printing, robotics, big data analytics, AI, IoT, AR/VR, and laser scanning. However, the majority points to BIM and its associated integrative digital platforms as the dominant key driver. This conclusion rests not on frequency of mention alone but on BIM's central role in enabling interoperability, coordination, and

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integration across the digital, tool, and physical layers of the Construction 4.0 framework. Unlike production technologies such as MIC and 3DP, which deliver execution-stage efficiencies, BIM serves as the systemic backbone that connects design, planning, execution, and data feedback, thereby enabling other technologies to generate value. Technologies such as MIC, 3DP, robotics, and automation exert influence through BIM-enabled integration rather than independently, confirming their role as secondary or complementary drivers. This aligns with prior studies that identified BIM as a central enabler of collaboration and data-driven decision-making while advanced production technologies deliver benefits only when digitally coordinated [21[35,36]. Digital technologies can be used to resolve disputes within the construction industry [37]. Importantly, while MIC and 3DP were frequently highlighted as impactful technologies for reducing construction time, waste, and labour dependency, their effectiveness remains conditional on the maturity of the digital layer [38]. Without BIM-enabled digital twins, data repositories, and coordinated planning environments, these technologies risk operating as isolated innovations rather than transformation drivers. The identification of BIM as the key driver, therefore, reflects not technological superiority but integration readiness and scalability within the South African context. Advanced tools such as blockchain, digital twins, big data analytics, and generative AI further reinforce this hierarchy, as their value is realised primarily through BIM-centred digital ecosystems [38,39[40]). Thus, the findings conclude that BIM supported by integrated digital platforms constitutes the key driver technology for digital transformation in South Africa, as evidenced by the study, the cross-theme qualitative synthesis, and the theoretical alignment with Construction 4.0 principles.

7. Conclusions, Implications, and Limitations of the Study

Based on extant literature and this study’s findings, understanding the role of emerging digital technologies, such as MS Project, BIM, IoT, sensors, drones, AI, cloud computing, and communication tools as key drivers of digital transformation in Construction 4.0 Adoption in the South African construction sector cannot be overemphasised. They would significantly accelerate the transformation of practitioners through reshaping production processes, addressing construction project disruptions, improving operations, enhancing construction project resilience, and delivery methods. This is critical for fast-growing, developing economies. Thus, attracting considerable attention from both practitioners and researchers in South Africa’s construction industry context, and supported by UTAUT 3, which will assist in improving Construction 4.0 implementation. The findings identified the technologies which are key drivers of digital transformation in Construction 4.0 Adoption in the South African construction sector into six sub-themes. This includes ideal physical digital technology to minimise delays, impact on projects in using MIC or 3DP, key driver technology during construction, the ability of BIM to pair with other digital tools, tools to be utilised in the “digital” layer, and digital tools to be utilised in the “physical” layer. Findings also clustered the use of digital technologies in construction project implementation into: digital tools essential to consultants and contractors; tools for design coordination, clash detection, and accurate planning; tools to increase efficiency; and the utilisation of digital technologies across construction project stages.

As part of this study’s implications, it will contribute to emerging digital technologies and theories, particularly UTAUT3, as described in Section 3. The adopted theory integrates human variables, firm readiness, and technological conditions; it provides a stronger basis for developing emerging digital technologies (Liu and Wang, 2026), which can transform the process model and support the implementation of Construction 4.0. UTAUT3 helps interpret how digital technologies create value, shape firm capabilities, and ultimately contribute to the manifestation of Construction 4.0 [17]. From a theoretical standpoint, this aligns with the performance expectancy concept in the UTAUT, which posits that technologies perceived as improving job performance are more readily adopted (Venkatesh et al., 2003). Regarding the practical implications, the research offers insights into how technology can be enhanced as a primary driver of digital transformation in the sector’s adoption of Construction 4.0. Although the study was conducted in South Africa, covering major provinces, the findings are methodologically generalisable to other developing African countries with similar infrastructural, economic, and legal features, particularly those in Southern Africa. This broader applicability is supported by in-depth literature, robust triangulation of findings across disciplines, and the identification of common ground to explore the scalable role of digital technologies in wider contexts. Finally, the study offers the construction industry's practitioners a structured approach to improving the efficiency of the system. The integration of digital tools would mitigate construction project delays and cost overruns, enhance collaboration and transparency, and accelerate on-site and off-site construction activities, thereby directly enabling a Construction 4.0 environment.

It implies that this research addresses key issues that have been lingering in the industry and bridges a gap between theory and practice by offering a benchmark to guide future research on the role of technology as a primary driver of digital transformation in Construction 4.0 adoption, using a qualitative approach in other third-world countries, offering insights for advanced countries. The research data may not fully reflect the digital technology adoption scenario in the rural areas of the provinces covered. The study may also have underrepresented ICT experts and government regulators, thereby limiting the generalisability of the findings. The multidisciplinary experts engaged may influence the consistency and depth of responses related to their effectiveness through a qualitative research design. The researchers proposed that future studies should expand the data collection mechanisms via a mixed methods approach to improve findings generalisation and inclusiveness.

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