

RESEARCH PAPER

Sustainable Roads for Sub-Saharan Africa: A Hybrid Construction 4.0 Approach

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Abstract

Sub-Saharan economies face critical infrastructure deficits, including frameworks for adopting Construction 4.0 technologies in road development. This study addresses this gap by developing structured Hybrid Construction 4.0 adoption pathways tailored to resource-constrained contexts.

Through semi-structured interviews with 30 Ghanaian construction experts, comprising construction engineers, project managers, local contractors, and road governing professionals, the study identified six compatible technologies: (i) BIM integrated with local norms and materials, (ii) mobile project management apps combined with manual supervision, (iii) low-cost IoT sensors embedded in indigenous subgrade materials, (iv) drones/UAVs supported by traditional surveys and community insights, (v) GIS/satellite data harmonized with local land-use knowledge, and (vi) modular mobile labs for on-site testing. The study further delineates distinct, cost-effective technology progression sequences for road typologies and firm sizes, advocating for a gradual transition that maximizes return on investment and minimizes operational disruption. This endeavour provides a novel-empirically driven framework for HC4.0 adoption, moving beyond theoretical barriers to offer a pragmatic, scalable pathway. By focusing on technological hybridization and phased sequencing within the specific socioeconomic and infrastructural realities of Sub-Saharan economies, this study offers a replicable model for sustainable infrastructure modernization in developing countries.

Keywords: Hybrid Construction 4.0, Sustainable Infrastructure, Road Construction, Technological Hybridization, Sub-Saharan economies.

1. INTRODUCTION

Integrating industrial revolution models into construction has proven challenging (Forcael et al., 2020), as technological advancements reshape methods and practices to enhance productivity (Maskuriy et al., 2019). Although Industry 4.0 remains highly relevant and is still being implemented across various sectors, the concept of Industry 5.0 has emerged more recently. While highly industrialized economies are gradually adopting Industry 5.0, many countries in Sub-Saharan Africa, including Ghana, continue to struggle with the implementation of Industry 4.0 (Mourtzis et al., 2022; Grosse et al., 2023). In the same vein, Construction 4.0 (C4.0) exists as an offshoot of Industry 4.0, indicating the construction landscape's ability to adapt and embrace the transformation (Berger, 2016; Rojko, 2017).

Globally, the construction industry faces mounting pressure to optimize its practices through digital transformation, with Construction 4.0 technologies offering unprecedented opportunities for productivity enhancement, waste reduction, and improved project outcomes (Sawhney et al., 2020). Advanced economies in North America, Europe, and East Asia have made significant strides in adopting Building Information Modeling (BIM), Internet of Things (IoT) sensors, Artificial Intelligence (AI), and

Augmented/Virtual Reality (AR/VR) technologies (Brozovsky et al., 2024; Yang, 2025; Fathi et al., 2025). These innovations have collectively delivered measurable gains: reducing project costs by up to 20%, shortening delivery timelines by about 10%, improving site safety by 25%, and decreasing equipment downtime by 40% (Vantighem et al., 2020; Bamigboye and Kirgiz, 2025). Moreover, AI-driven predictive analytics now forecast project delays with over 80% accuracy, while AR/VR applications enhance stakeholder engagement and on-site training, cutting rework rates by approximately 15%. (Maskuriy et al., 2019; Bamigboye and Kirgiz, 2025). These achievements have been enabled by robust digital infrastructure, substantial capital availability, highly skilled workforces, political domain, and supportive regulatory frameworks that facilitate technology integration (Jaafar et al., 2025; Souza et al., 2025). However, a recent study demonstrates that Construction 4.0 adoption challenges are fundamentally different across economic contexts (Turkyilmaz et al., 2024), with developing nations facing unique barriers that are not adequately addressed by frameworks developed for industrialized economies (Mansour et al., 2023).

Across African countries, construction industries grapple with distinct challenges that render direct technology adoption problematic (Ibrahim et al., 2024; Biney et al., 2025a). Hajj et al. (2021) and Ojbanire et al. (2025) found high implementation costs and resistance to change as key Industry 4.0 adoption challenges in North Africa. Within the Global South, Africa and South America represent a particularly underexplored region in Construction 4.0 discourse, with only 30% of published research on digital construction technologies, indicating geographical disparity in the application of these technologies (Brozovsky et al., 2024; Souza et al., 2025). A study by Olatunde et al. (2022) revealed that the adoption level of Construction 4.0 in Nigeria is at a low level, owing to the lack of investments in research and development and the cost of implementation. Similarly, Osunsanmi et al. (2018a) and Ibrahim et al. (2024) assert that the cost of investing in modern technology by small construction firms is a conspicuous hindrance to the adoption of construction 4.0 in South Africa, Nigeria, and Ghana. Consequently, as Perera et al. (2023) and Souza et al. (2025) note the existence of a practical implementation gap in the adoption of Construction 4.0, it is pertinent to explore cost-effective and context-specific models that facilitate the gradual and sustainable adoption of digital technologies within resource-constrained environments such as Sub-Saharan Africa.

The Ghanaian Road construction industry has a profound impact on economic development, as reflected in the data from the Ministry of Finance's 2025 budget statement. As with many other Sub-Saharan economies, Ghanaian road systems are crippled by issues such as poor road networks, traffic congestion, and inadequate infrastructure (Marteye et al., 2018; Odonkor et al., 2020). Studies show that Ghanaian public construction projects typically experience estimated cost overruns of 40% above the initial budget and 62% time overruns (Laryea, 2010; Owusu et al., 2020; Adusei et al., 2024). These inefficiencies point to the need for sustainable construction approaches such as the hybrid Construction 4.0.

Existing literature extensively documents barriers to Construction 4.0 implementation in developing countries (Ibrahim et al., 2024; Pittri et al., 2025); however, this barrier-focused research has not translated into actionable adoption pathways. A systematic review of 141 studies on Construction 4.0 highlights that the majority of focus has been on identifying barriers, challenges, and opportunities, revealing that few studies propose structured implementation frameworks, while none provide empirically validated, context-specific progression sequences for phased technology adoption (Souza et al., 2025; Hajirasouli et al., 2025). This represents a critical translation gap between problem identification and practical implementation (Souza et al., 2025). Despite perceived indications of an upsurge in the integration of building information modelling (BIM) within the broader Ghanaian construction horizon, the industry still has not fully imbibed the C4.0 concept into operations. It is therefore pertinent to investigate how C4.0 could transform the construction and management of road projects in Sub-Saharan economies from the Ghanaian perspective.

The concept of hybrid models, specifically, Hybrid Construction 4.0 (HC4.0), the strategic integration of digital technologies with core traditional construction methods or human-related factors, has been conceptually advocated in recent literature but lacks empirical operationalization and implementation (Soltani et al., 2023; Hajirasouli et al., 2025). While scholars acknowledge the importance of considering both technological and human-related factors in the adoption of hybrid models for construction 4.0, no studies have systematically identified which specific digital-traditional technology combinations are compatible with local construction practices, material systems, and institutional frameworks in Sub-Saharan Africa. Furthermore, existing research has not addressed how technology adoption pathways should differ based on project scale and contractor capacity, despite evidence that firm size significantly influences technology absorption capacity in construction (Shams et al., 2025). The absence of validated,

scalable HC4.0 frameworks perpetuates ad-hoc technology adoption attempts that frequently fail to achieve return on investment or sustainable integration into construction workflows.

The lack of empirical evidence of a structured pathway for the adoption of these models adds to compounding factors. This study aims to address this gap by (i) identifying compatible digital-traditional technology for Ghana’s road landscape, and (ii) determining viable technology in progression sequences for different contract sizes in Ghana’s road construction industry. By addressing the technical compatibility and knowledge hybridization of these composite technology models for adoption, this research contributes to the existing body of knowledge and thus provides a robust underpinning for developing progression pathways for advanced construction technologies adoption.

2. LITERATURE REVIEW

2.1 Construction 4.0

The paradigm shift towards advanced construction technologies presents an interesting transformational possibility when it takes full course. Ghana’s road development odyssey has seen remarkable progress since its inception, influenced by changing economic policies, political tenures, and the country’s yearning to achieve sustainable development (Akinradewo et al., 2020; Walther et al., 2024). Although Ghana has made considerable headway in embracing these modern technologies and practices, its adoption trajectory differs from the linear progression observed in highly industrialized nations. Green construction is experiencing a nascent yet pronounced growth within the Ghanaian built environment, particularly in its capital, Accra (IFC, 2022). The adoption of BIM within the construction industry continues to be the leading C4.0 technology in practice, albeit at a slow pace due to the limitations of the Public Procurement Act (PPA), which primarily favours the traditional procurement system. The applications of prefabrication and modular construction techniques are another area that has been embraced by the industry (Wuni and Shen, 2019; Biney et al., 2025b).

Long accustomed to humans handling complex tasks in the construction community, the emergence of self-governing robots provides a more extensive scope for construction and management (Li et al., 2024). Mohsan et al. (2023) discuss the employment of unmanned aerial vehicles (UAVs) for site surveying, progress monitoring, and inspection purposes, providing real-time data from otherwise inaccessible areas. As a consequence of these applications, digital road models and prototypes have been created, incorporating data on design, materials, and processes while promoting sustainability (Haverkamp et al., 20258). Better visualization of road alignments, construction sequencing, and identification of potential conflicts are results of the applications of the simulation concept within the C4.0 framework (Rashidi and Karan, 2018). The Internet of Things (IoT), since its introduction in road construction, has further amplified productivity and efficiency. Katiyar and Kumar (2021) highlighted its appositeness in asset tracking, traffic management, and predictive maintenance, while Ye (2024) underscored the use of smart sensors for real-time, unceasing monitoring of road conditions. Machine learning (ML), a subdivision of artificial intelligence (AI), has shown promise in predicting road surface conditions based on weather data for maintenance planning (Abioye et al., 2021). The realization of the prospect of these technological developments and the resulting efficient and sustainable outcomes heightens the need for a paradigm shift.

Table 1. Construction 4.0 Applications in Road Construction and Management

Technology	Application Area	Function	Expected Benefits
Simulation	Design/Planning	Drones	Road Investigation, Road Vegetation Management
		BIM	3D Design Models
		VR/AR	Immersive Simulation of Road Designs
		Digital twin	Design Optimization
	Construction	Construction Process Simulation	Prevent bottlenecks/simulation
		3D Printing	Additive manufacturing
		AR/VR	Overlay virtual element onto the site, Real-time information and instructions
	Maintenance	Digital twin	Maintenance Design Optimization
		BIM	Expansion update, asset management, Progress Monitoring
		3D Printing	Road maintenance

Source: (Authors’ construct, 2025)

Tables 1, 2, and 3 provide an overview of C4.0 applications in road projects. These applications are catalogued into Oesterreich and Teuteberg's (2016) three conceptual dimensions of C4.0. Oesterreich and Teuteberg (2016), one of the early proponents of the C4.0 paradigm, catalogued the concept into three main branches, namely simulation, virtualization, and smart site.

Table 2. Construction 4.0 Applications in Road Construction and Management

Technology	Application Area	Function	Expected Benefits
Smart Site	Design/Planning	IoT	Real-time data design process monitoring
		Geographic Information System (GIS)	Spatial Analysis
	Construction	IoT	Quality Control/Monitoring, Real-time monitoring
		Robotics and Automation	Construction Process
		RFID	Equipment monitoring, Proximity sensing and safety, Material tracking
	Maintenance	AI/ML/Data Analytics	Schedule monitoring, Site Management
		IoT	Predict road distress, Vegetation encroachment, Remote Monitoring, and Road assets assessment.
		ITS	Smart solutions, Traffic flow, Advanced traffic management
		RFID	Leakage monitoring, Proximity sensing, Traffic condition detection, Vibration monitoring
		AI/ML/Data Analytics	Predictive maintenance, Passenger flow forecast, Road assessment

Source: (Authors' construct, 2025)

Table 3. Construction 4.0 Applications in Road Construction and Management

Technology	Application Area	Function	Expected Benefits
Virtualization	Design/Planning	Cloud-Based Collaboration Platforms	Real-time information sharing on design data
		Virtual Design Construction	Assess design performance, simulate construction sequences.
		Cloud-based analytics	Real-time access to the design stage data.
	Construction	Cloud-based project management systems	Real-time information sharing on project data
		Mobile Applications and Cloud Integration	On-site data information, Real-time monitoring
		Virtual Commissioning	Optimize complex systems, traffic management systems, and Signal synchronization.
	Maintenance	Cloud-based asset management systems	Real-time information sharing on project maintenance data
		Remote Monitoring and Diagnostics	Predict failures, Schedule maintenance.
		Cloud-based Predictive Analytics	Predictive Maintenance

Source: (Authors' construct, 2025)

2.2 Hybrid Construction 4.0 Technologies

Sub-Saharan economies, amidst a myriad of challenges hindering the transition, hybrid construction 4.0 (HC4.0) represents a pragmatic paradigm shift within the construction landscape. HC4.0 focuses on the strategic integration of advanced C4.0 technologies with established traditional construction methods and indigenous knowledge systems. This model embraces the dual strength of modern efficiency and local expertise, moving beyond simplistic, wholesale replacement of conventional practices with sophisticated, advanced tools that may not be practical and economically prohibitive in the Sub-Saharan region. With a focused synergistic adaptation of contextual realities, Osunsanmi et al. (2018b) explain that HC4.0 and selective C4.0 implementation offer maximum value, improve stakeholder engagement, and minimize capital expenditure while consciously retaining and enhancing proven traditional techniques. Maisiri et al. (2021) assert the potency of HC4.0 to navigate infrastructure deficits, a plight that is common in the Sub-Saharan region. In the implementation of HC4.0, there is a profound emphasis on contextual adaptation, prioritizing flexibility, cost-effectiveness while promoting sustainable capacity building.

The integration of BIM with the manual construction process represents perhaps the most prevalent hybrid approach in industry circles across Sub-Saharan Africa. Wuni and Shen (2019) note that while the sophisticated digital modelling capacity of BIM is employed for design coordination, manual labour is largely responsible for actual construction. This approach utilizes existing workforce competencies,

maintains employment levels while reducing design errors. Even so, Appiah's (2020) critical appraisal reveals several limitations in their current application. The typical BIM-manual hybrid only harnesses 35-40% of BIM's potential value creation (Appiah, 2020). This partial realization of value is enabled by the information silos generated by the digital-physical divide; design intelligence is held within digital models while construction carries on through conventional means. Kissi et al. (2023), moreover, posit that existing hybrid approaches in Ghana do not employ systematic integration frameworks, thereby rendering ad-hoc implementations failing to optimize the synergy between digital and traditional elements. The coupling of IoT technologies with indigenous materials is another hybrid model gaining traction. Here, smart sensors are deployed to monitor the structural health of road infrastructure constructed from locally sourced materials such as laterite and gravel. Edirisinghe's (2019) optimistic assessment of smart sensors with local materials overlooks the fundamental infrastructure requirements of developing economies: internet connectivity, power supply, and technical maintenance capabilities. Given the several convergent factors such as infrastructural gaps, limited financial resources, and the rich indigenous knowledge base in the Sub-Saharan region, the adoption of HC4.0 offers a game-changing solution. HC4.0 provides the possibility of sequential technology adoption, thereby permitting firms to start with high-impact, more affordable digital solutions. A crucial driver in HC4.0 is its cost-effectiveness, as the phased technology adoption reduces the high upfront investments that would otherwise be needed in widescale displacement. The phased approach enables institutions to reap immediate productivity benefits while building technological capacity incrementally. Studies show that the Sub-Saharan construction landscape possesses a large, experienced workforce skilled in traditional construction methods (Tetteh-Agblakah, 2025), and this would be economically wasteful to displace entirely. Additionally, with full implementation of C4.0 projected to require lengthy years for adoption in developing countries (Tetteh-Agblakah, 2025), hybrid approaches can deliver immediate productivity. This blend of digital technology with the traditionally entrenched workforce competencies can minimize the retraining requirements that often accompany wholesale technological transformation while preserving valuable institutional knowledge. The synergy between sustainability and HC4.0 particularly aligns with the region's developmental priorities and environmental agenda. The abundance of natural materials, including bamboo, laterite, and gravel in Sub-Saharan regions such as Ghana, presents an economical approach to monitoring the structural health of roads when combined with IoT sensors, while promoting local material supply chains. Currently, several gaps exist in the realization of HC4.0 models. There is a lack of scalability frameworks for phased adoption across contractors of varying sizes in the Sub-Saharan climate (Adepoju and Aigbavboa, 2020). Additionally, few empirical studies are validating hybrid workflows in these economies. Policy barriers continue to remain largely unaddressed, hindering stakeholder-driven hybrid modeling efforts (Appiah, 2020).

2.3 Theoretical Anchors

HC4.0, positioning hybridization as a pragmatic pathway to construction modernization, is established on foundational principles that demonstrate how selective technology integration can achieve productivity while avoiding the exorbitant wholesale displacement (Osunsanmi et al., 2018b; Maisiri et al., 2021; Kissi et al., 2023). The theoretical underpinnings of HC4.0 rest on a few interconnected theoretical pillars: Technology Appropriateness Theory, Knowledge Integration Theory, Rogers' Diffusion of Innovations Theory, and Adaptive Implementation Theory. Drawing upon the idea of intermediate technology by Schumacher (1973), the Technology Appropriateness Theory contends that optimal technological solutions ought to be congruent with the domestic economic environment, skills, and infrastructural capacities. HC4.0 is uniquely positioned within this theory as the selective technology process translates to cost-benefit balance vis-a-vis technological innovation (Osunsanmi et al., 2018b; Perrier et al., 2024).

The selective C4.0 integration associated with HC4.0 creates contextually relevant solutions that leverage both computational efficiency and local expertise. This aligns with the knowledge integration theory, which takes precedence from Nonaka and Takeuchi's (1995) knowledge creation framework, emphasizing the synthesis of explicit digital knowledge with tacit indigenous construction wisdom (Glass, 2005). This is corroborated by Maisiri et al. (2021)'s assertion of HC4.0 being more sustainable through knowledge hybridization rather than knowledge replacement. HC4.0 augments Rogers' Diffusion of Innovations theory (2003), where hybridity acts as a compatibility bridge easing technology assimilation in resource-constrained contexts (Osunsanmi et al., 2018b; Olatunde et al., 2022; Khurshid et al., 2023). As compared to linear C4.0 adoption models appropriate for developed economies, HC4.0 requires elastic, iterative execution models capable of adapting to changing situations while still progressing (Adepoju and Aigbavboa, 2020). This aligns strongly with the adaptive implementation theory that recognizes that

technology adoption within emerging markets occurs on a non-linear trajectory influenced by resource availability, institutional strengths, and market demand (Murguia et al., 2024).

3. RESEARCH METHODOLOGY

The nature of the study informed the use of the qualitative research design guided by the interpretive paradigm (Darby et al., 2019). This design was adopted because the study sought to explore the subjective interpretations and experiences of construction professionals in adopting Hybrid Construction 4.0 (HC4.0) technologies for sustainable roads. The interpretive paradigm enabled the researchers to capture meanings, values, contextual nuances underpinning technology hybridization and phased adoption sequences based on their contextual realities, which cannot be fully understood through quantitative measures. The nature of HC4.0 demands deep contextual inquiry into human–technology interactions, institutional frameworks, and local construction practices, all of which are better elicited through qualitative approaches (Zheng et al., 2025).

This enabled the authors to utilize framework analysis as the analytical strategy, which provides systematic rigor while maintaining the flexibility needed to capture emergent themes within pre-defined research objectives (Gale et al., 2013). The framework analysis, as detailed by Walther et al. (2012), enabled structured coding and theme development while preserving contextual depth. To tap into the collective expertise of professionals who possess advanced technical capabilities and managerial experience, the purposive sampling technique was employed (Elbardan and Kholeif, 2017). This approach allowed the inclusion of participants with direct experience in hybrid digital–traditional construction processes, ensuring that data were drawn from information-rich cases (Tajik et al., 2024; Bouncken et al., 2025). The method enabled the recruitment of 30 interviewees across three stakeholder groups, namely (i) construction engineers and project managers, (ii) local contractors, and (iii) road governing professionals. Thematic saturation was systematically monitored throughout the data collection process following established protocols (Sebele-Mpofu, 2020; Hennink and Kaiser, 2022). The research team documented the emergence of new themes after each interview to track saturation progression. The thematic saturation was achieved after 27 interviews, with interviews 25, 26, and 27 producing no additional themes beyond those already identified. To ensure robustness, three additional interviews (interviews 28, 29, and 30) were conducted as validation interviews, which confirmed that the coding framework had captured the full dimensionality of participants' perspectives (Hennink and Kaiser, 2022). As characteristic of qualitative and grounded theory research, the sample size of 30 participants is within Wutich et al. (2024)'s threshold necessary to fully explore and realize complete dimensionality.

Acknowledging the limitations in extrapolating findings beyond the sampled population, deliberate sample diversification was applied across organization types, project scales, and geographical regions to ensure the validity of the responses. To ensure representativeness, contractor selection followed the Ministry of Roads and Highways (2023) classification system, which categorizes firms by both technical and financial capacity. This approach yielded four distinct contractor categories: A4B4, A3B3, A2B2, and A1B1. Each group was adequately represented, with A4B4 and A3B3 comprising 5 participants each, and A2B2 and A1B1 comprising 7 participants each. Additionally, the inclusion of road governing professionals, consisting of 6 participants, was necessary to capture policy and regulatory perspectives, ensuring that the proposed hybrid technology pathways align with institutional frameworks and governance realities. Prior to data collection, ethical approval was obtained from an institutional review board, and interviews were initiated only after participants confirmed via email their comprehension of data usage, storage, risk disclosure, and anonymity assurances. Pseudonymization was applied during transcription (e.g., "CE1" for engineer), which, according to Kohlmayer (2019), safeguards anonymity, given the potential commercial sensitivities surrounding technology adoption and business practices. The 50–60-minute process was conducted via Microsoft Teams by Patton's (1960) general qualitative interview guide. These sessions were centered on current construction practices, technology integration experiences, local material, climate considerations, and perceived optimal hybrid combinations. The coding process generated a hierarchical structure consisting of 127 initial codes, which were subsequently organized into 18 sub-themes, and ultimately consolidated into 6 main themes for the first research objective (compatible HC4.0 technologies) and 3 overarching themes representing the progression phases for the second research objective (technology adoption sequences). The initial 127 codes captured granular elements of participants' descriptions of technology applications, integration challenges, cost considerations, and contextual factors. These were inductively grouped into sub-themes based on conceptual similarity and

functional relationships (Braun and Clarke, 2019). The 18 sub-themes were then deductively mapped against the study's theoretical framework and research objectives to derive the final thematic structure.

In line with Ritchie and Spencer's (1994) framework analysis, the data were analyzed within pre-determined research objectives while maintaining flexibility for emerging themes. The coding process followed a hybrid approach combining inductive and deductive strategies to balance theoretical sensitivity with data-driven discovery (Fereday and Muir-Cochrane, 2006). This was followed by an indexing and coding phase, primarily done using NVivo 14 software (Bergin, 2011). The initial coding phase employed open coding techniques, which, according to Campbell et al. (2021), is where two independent coders systematically review transcripts line-by-line to identify meaningful units of text related to technology compatibility, implementation experiences, and adoption barriers. A preliminary codebook developed after the first five transcripts served as a modifiable template for subsequent analysis (MacQueen et al., 2020). The examination of data began with a thorough and repeated reading of transcripts, through to thematic framework identification based on the research objectives and emerging concepts. Axial coding then examined relationships among initial codes to identify patterns and hierarchical structures, grouping functionally similar codes into sub-themes informed by both data patterns and the study's theoretical anchors (Charmaz, 2020; Thornberg and Charmaz, 2014). Selective coding integrated sub-themes into overarching thematic categories addressing the research objectives through constant comparison across stakeholder groups and project scales (Corbin and Strauss, 2015; Boeije, 2002). Themes were refined iteratively, examining negative cases to ensure internal homogeneity and external heterogeneity (Patton, 2015). 20% of the transcripts were subjected to independent coding by two independent coders to establish inter-coder reliability. With an 83% agreement on the initial round, disagreements were resolved through discussion and refinement of coding criteria by all the authors (O'Connor and Joffe, 2020).

The data underwent a two-step validation process to ensure the technical feasibility and relevance of the proposed hybrid models. First, triangulation across 5 selected participants from each stakeholder category was conducted to verify interpretation accuracy (Sousa et al., 2018). Second, a Delphi exercise involving ten Sub-Saharan regional experts in construction technology was carried out over two iterative rounds. In round 1, experts individually reviewed the six hybrid models and progression sequences, providing structured feedback on feasibility, scalability, and contextual appropriateness. Responses were collated and anonymized, with thematic refinements incorporated. In round 2, anonymized feedback was consolidated and redistributed, enabling experts to revise their positions until consensus was achieved on core elements of the adoption pathways. Consensus was defined as greater than 70% agreement on feasibility, sequence logic, and contextual fit, consistent with Delphi best practice (Hsu and Sandford, 2007), and the iterative feedback loop confirmed the framework's applicability, aligning with established protocols (Tilakasiri, 2012) while ensuring both theoretical soundness and practitioner endorsement.

4. FINDINGS

4.1 Demographic Profile

Determined by both theoretical saturation principles and stakeholder representation requirements, the distribution as indicated in Table 4 showed a deliberate diversification of the sample. This distribution is also reflective of Ghana's road construction ecosystem, where technical professionals outnumber regulatory personnel. While the 6 road governing professionals represented both policy and procurement practitioners, the 24 selected contractors and technical professionals spanned across the three MORH's (2025) organisational classifications. Table 4 further shows the occupational codes under which stakeholders were categorised during the coding structure preparation.

Table 4. Demographic Profile of the Interview Participants

Stakeholder Group	Stakeholder Group Codes	Nos.	Avg. Years of Experience	Project Type Expertise
Construction Engineers and Project Managers	CE	3 (A1B1) 4 (A2B2) 3 (A3B3) 2 (A4B4)	20	Highways (60%); Urban (40%)
Local contractors	LC	4 (A1B1) 3 (A2B2) 2 (A3B3) 3 (A4B4)	18	Rural (70%); Bridges (30%)
Road governing professionals	RP	6	20	Policy and Procurement (100%)

4.2 Thematic Analysis

4.2.1 Objective One: Identifying Compatible Digital-Traditional Technologies for Ghana's Road Landscape

The thematic analysis of interviewed data revealed six prevalent themes that stakeholders deem as compatible digital-traditional technologies for Ghana's road construction, validated through triangulation and expert consultation.

Theme 1: Digital Tools as Translators of Local Material Behaviour: Experts indicated the compatibility of integrating BIM with indigenous construction norms and materials such as laterite, bamboo, and gravel to optimize designs while promoting local material supply chains. LC 3 emphasized that while BIM's digital modelling power enables simulation of laterite compaction rates under specific rainfall patterns, considerations often overlooked in manual design, the hybrid approach deliberately retains reliance on local masons' expertise in gravel sourcing to prevent over-engineering and cost escalation. There was a widely held belief among stakeholders on the compatibility of BIM and manual execution as a hybrid technology in Ghana's landscape. A civil engineer (CE1) mentioned that digital tools such as BIM and project management software were recognised for their capacity to address material performance uncertainties of locally sourced gravels and laterite during the design phase, with traditional construction methods and on-site craftsmanship subsequently managing the physical execution process. This reduces technology adoption barriers by limiting digital requirements to planning phases while maintaining familiar on-site workflows. It is a gradual adoption pathway where technology enhances rather than replaces existing competencies, especially when one of Sub-Saharan Africa's technology barriers is resistance to change. A regulatory governing professional noted BIM's prevalence in industry circles makes it readily combinable with existing practices, offering 3D visualisation capabilities that guide unskilled or semi-skilled labour on traditional builds, enabling workers to comprehend complex designs without requiring full architectural training while preserving their hands-on construction expertise (RP8). This is crucial for Sub-Saharan contexts where labour is available but formal training is limited.

Theme 2: Adaptive Digitalization Under Infrastructural Constraints: Stakeholders emphasized the viability of combining low-data or offline operable mobile project management apps with the traditional face-to-face supervision and accountability systems. They indicated that with the lack of digital infrastructure, especially in rural areas, such an approach enables project managers and superintending officers to track progress and issues digitally.

Given Ghana's road construction projects are characterised by remote locations, seasonal weather disruptions, and limited internet access, offline project management tools were described as transformative for tracking progress and documenting deliveries, though the traditional inspection protocols and physical presence of senior engineers remain vital for ensuring compliance with engineering standards and making contextual judgements that digital reporting alone cannot capture (RP6, CE4). A local contractor (LC11) added that the involvement of human-related factors in this hybrid model can enable field planners to document informal settlements, track infrastructure development, and coordinate with community leaders. This approach reflects the gradual integration of technology without displacing essential human oversight.

Theme 3: Embedding Community Knowledge into Technological Workflows: A local contractor noted that embedding IoT sensors in sub-base layers of locally sourced gravels or laterites, which vary in performance by quarry based on indigenous knowledge of material sources, could provide digital alerts when compaction thresholds dip, while explicitly maintaining visual inspection protocols by experienced technicians and manual execution procedures for emergency repairs that require human judgment and traditional repair techniques (LC8). Similarly, engineers envisioned installing vibration sensors in laterite or gravel subgrades to monitor structural health amidst moisture, load, and wear, with database synchronization occurring when field crews return to towns, eliminating the need for constant internet connectivity while preserving the field crews' hands-on maintenance practices and local knowledge of material behaviour (CE9).

While a considerable few cautioned about the need for robust infrastructure to ensure a smooth operation, there was a consensus among several experts on how adaptable this hybrid approach is in the interim for Ghanaian road construction. RP1 mentioned that the concept was deemed laudable and realistic, though concerns were raised regarding sensor durability under harsh weather conditions and the

need for robust data analytics systems necessitating human expertise involvement to interpret sensor data effectively. This approach underscores the pragmatic balance central to HC4.0, acknowledging that while digital tools add value, their effectiveness depends on local environmental adaptation and human analytical input.

Theme 4: Cost–Benefit Rationalities Driving Hybridization: Interviewees also noted the viability of combining low-cost drones (UAVs) with the orthodox site surveying techniques. Road governing professionals emphasized that integrating low-cost drones with traditional manual ground survey processes performed by experienced surveyors enhances accuracy while reducing costs, proving particularly valuable in difficult terrain situations where traditional surveying instruments are lacking but where human interpretation of site conditions remains essential (RP2; RP4). The hybrid solution was recognized for elevating data accuracy and road plans through high-resolution imagery and topographic data production from UAVs, complemented by the precision and ground-truthing capabilities of manual survey techniques (LC7). Some practitioners cited this as a classic example of hybrid Construction 4.0 already being practised by a few companies, noting huge revolutionary potential when scaled up and encouraging adoption efforts that maintain the balance between digital efficiency and surveyor expertise (CE3). Beyond technical advantages, experts valued how drones map slopes rapidly while traditional knowledge of seasonal flooding patterns and sacred lands, obtained through direct consultation and relationship-building with village chiefs and communities, informs route optimisation around flood-prone zones tracked for generations through oral history and lived experience, complementing capabilities that technology alone cannot replicate (CE5).

Theme 5: Toward a Predictive Maintenance Culture: This hybrid technology also surfaced among several interviews as having the potential to improve community engagement and participation while improving accuracy in road planning and design. A civil engineer (CE10) highlighted that the concept of combining GIS and satellite data with indigenous land use knowledge gathered through community consultation was described as revolutionary, harbouring merits that ensure roads withstand local environmental conditions while minimizing maintenance costs and helping practitioners identify potential bottlenecks, though accurate translation of indigenous knowledge held by local communities into technical specifications and designs through participatory processes remains essential and sustainable. The hybrid approach creates comprehensive site intelligence by merging data-driven precision with lived experience. The emphasis on accurate translation through participatory processes ensures gradual adoption by making communities active contributors rather than passive recipients, preventing technology from imposing foreign solutions that ignore local realities, CE 10 further added. Local contractors (LC 3) and (LC 5) noted that geospatial tools combined with community-driven land use knowledge and traditional spatial knowledge enable early insights on road conditions and traffic patterns. Beyond engineering benefits, this hybrid model enhances community engagement by directly involving local stakeholders, contingent on offline capability or low-bandwidth optimization that respects digital infrastructure limitations while facilitating human interaction for adoption (LC 3; LC 5).

Given Sub-Saharan Africa's fiscal constraints in road construction, this practical hybrid model is essential for ensuring sustainable and resilient systems that prioritise community needs and interests through meaningful engagement. However, implementation depends on actively involving local communities in planning processes, integrating their experiential knowledge and cultural perspectives with modern technological tools through established guidelines (RP3). This approach highlights HC4.0's inclusive and socially adaptive character, ensuring that technological tools evolve in partnership with community input and cultural context.

Theme 6: On-Site Testing as a Pathway to Immediate Quality Assurance: Experts also indicated the feasibility of truck-mounted site laboratories to enable on-field testing and analysis of materials. The on-site hybrid workflow of integrating modular mobile labs was recognized for deeply enhancing the existing construction process by bringing laboratory testing capabilities directly to construction sites, where traditional material testing and quality control have historically relied on experienced technicians' hands-on assessment and visual inspection (CE8).

There was considerable caution about the nature of these modular labs to be able to withstand Ghana's weather conditions. Truck-mounted site labs operated by technicians trained in both digital analytical tools and manual compaction tests that draw on traditional testing methods were described as potentially ground-breaking in Ghana's road infrastructure, enabling data-driven decisions that

complement field technicians' experiential knowledge while reducing delays and costs associated with sending samples to distant laboratories, though the nature and material composition of these labs require prioritisation to ensure indoor occupancy comfort for professionals working in Ghana's tropical climate (RP2). A local contractor (LC 3) indicated that HC4.0's synergistic blend of digital precision and human expertise, where technicians integrate mobile on-site testing with traditional manual compaction testing. By combining data-driven insights with experiential judgement, this approach optimises technology adoption through progressive skill transfer, reduced resistance to change, and seamless alignment between digital innovation and established construction practices.

4.2.2 Objective Two: Viable Technology Progression Sequences for Contract Sizes

Guided by framework analysis, distinct technology adoption sequences across Ghana's road project typologies were developed. The progression was driven by cost threshold, local resource availability and accessibility, and technical capacity.

Progression Sequence for A3B3 and A4B4 contractors: Interviewees highlighted the need to establish simple and less costly tools, such as WhatsApp Business and Mobile GIS applications, as a start-up to the phased adoption approach. As these simple tools become routine, firms can then layer in more advanced solutions such as basic weather monitoring, rain gauges, IoT sensors, and renting UAV photogrammetry monthly.

Theme 1 (Foundation phase): Everyday Mobile Tools as Practical Entry Points

Respondents emphasized the ubiquity of mobile phone ownership among road construction professionals, making Mobile GIS apps practical for site surveys, particularly given their offline functionality for remote locations. WhatsApp groups were identified as effective platforms for stakeholder coordination while maintaining orthodox road construction processes (CE 8). For small road projects, mobile tools digitize documentation without capital strain, with GIS apps complementing normal construction processes and WhatsApp Business enhancing stakeholder participation rather than having to subscribe to an advanced stakeholder coordination application such as Construction Cloud. This approach reduces paper logs and saves both time and money (LC 5). By adhering to these suggested tools in the foundational phase, small-scale firms with limited financial and technical capabilities can gradually adopt Construction 4.0 technologies through a hybrid approach that leverages ubiquitous smartphone ownership and familiar platforms like WhatsApp and mobile GIS to digitise documentation and coordination while maintaining traditional construction methods, eliminating costly specialised software investments, and building digital readiness for subsequent technology phases.

Theme 2 (Consolidation phase) Layering Monitoring Tools on Established Digital Routines

After establishing stability with low-cost modern tools, projects can rent UAV photogrammetry monthly for erosion monitoring, complemented by local labour for drainage maintenance using indigenous flood-prone area knowledge (CE 9). Additionally, CE 9 added that triggers should be placed to ensure ROI realisation without taking high risks. Once mobile GIS and WhatsApp coordination systems become effective, firms can adopt basic low-cost IoT sensors for real-time monitoring of water levels on bridges and structural stress, feeding data directly to databases for immediate responses (RP 3). Metrics, such as earned value analysis, should be structured so that when projects exceed certain contract thresholds, scheduled and cost performance index calculations can guide the achievement of good ROIs despite higher washout risks. Local contractors can photograph work progress daily and upload directly to shared project boards or platforms, creating automatic documentation trails for quality assurance. Basic weather monitoring stations, including simple rain gauges connected to mobile apps, represent the logical next step after consolidation (LC 6). This phase enables firms with low financial and technical capabilities to adopt Construction 4.0 technologies through a hybrid construction 4.0 (HC4.0) progression sequence that layers affordable digital tools (mobile GIS, WhatsApp coordination, rented UAVs) onto existing traditional practices (local labour, indigenous knowledge, manual photography), allowing incremental technology adoption triggered by measurable ROI thresholds rather than requiring large upfront capital or specialised expertise.

Progression Sequence for A2B2 contractors: Road experts continue to insist on maintaining basic digital integration as the foundation and jumping point for medium-scale contracts. They propose

BIM and IoT sensors as the next step, leveraging BIM's prevalence in Ghana's landscape and the decreasing costs of IoT sensors. Finally, they suggest incorporating mobile site labs with a local material database as the final stage in the progression sequence.

Theme 1 (foundation phase): Basic Digital Integration

Respondents emphasised that, just as with small-scale contracts, medium-scale projects require strong foundations to achieve realistic ROI. Basic digital integration, such as WhatsApp Business for stakeholder coordination, and Mobile GIS apps, complements traditional construction techniques, serving as ideal starting points for gradual technology adoption (CE1). These practices were corroborated by LC 7, who highlighted the need for financial feasibility within the foundation stage to remain a top consideration despite the theoretical soundness of technological sequences. This phase was consistently identified as critical across all contract scales, as poor initial implementation strategies make it challenging to persuade investors or stakeholders to adopt advanced technologies, regardless of their transformative potential. Basic digital tools, including WhatsApp Business, GIS mobile applications, and offline project management software and databases, should be conveniently integrated into operations to enable the gradual technology adoption, given their minimal start-up costs and existing familiarity within the industry (LC 11).

Theme 2 (consolidation phase): BIM and IoT as Targeted Solutions

Participants indicated that Civil 3D and advanced 3D modelling tools enable faster design revisions, helping professionals identify clashes before breaking ground. With the application of BIM tools, drainage can be modelled while sensor data adjusts gravel ratios according to soil variability (CE 3). Additionally, CE 3 added that IoT moisture sensors for laterite subgrades address the unpredictable behaviour of laterite during rainy seasons, with real-time monitoring preventing costly failures. For peri-urban highways connecting to feeder road networks, IoT monitoring makes perfect sense as the next step after full integration of BIM in the first phase (RP 9). Once BIM establishes digital workflows and data management practices, adding IoT sensors becomes a natural extension rather than a completely new technological leap, making it a logical next step in gradual technology adoption. From an investment standpoint, the technological progression involving BIM and IoT offers significant advantages, with centralized material databases saving medium-scale projects substantial sums in preliminary investigations. One local contractor (LC 8) mentions that environmental monitoring IoT sensors facilitate EPA guideline compliance, while BIM remains, from anecdotal evidence, the most prevalent advanced technology in industry circles, making its combination with manual execution a logical progression. This second-phase hybrid approach gradually increases technology use through BIM design tools and IoT monitoring systems while traditional construction methods execute the physical work, enabling digital optimisation of materials and real-time quality control without disrupting established site practices.

Theme 3 (expansion phase): Mobile Site Labs for Predictive Maintenance and Quality Assurance.

Mobile laboratories address a significant industry operational challenge: quality assurance coverage. The cost-benefit becomes clear at this phase, as firms should have achieved significant ROI from earlier investments in the foundational and consolidation phases (CE 8). This finding was supported by LC 7, who mentioned that the immediate quality control potential of mobile laboratories represents a substantial improvement over current practices requiring 5–7 days for sample results from distant laboratories, during which additional subgrade may already have been laid. Pothole prediction algorithms could enhance maintenance approaches, steadily moving towards a predictive maintenance culture. For medium-scale projects, appreciable investment in this technology becomes realistic given stable ROI achievement during earlier phases (LC 7).

Progression Sequence for A1B1 contractors: Experts proposed a technological sequence that includes BIM and digital technologies as a baseline, followed by digital twins and IoT sensors for local material analysis, and culminating in AI-optimized machinery routing. Some indicated that this sequence has a high probability of yielding a full ROI after three projects through phased implementation.

Theme 1 (foundation phase): Integrating Basic Digital Tools with BIM as a Baseline

For large-scale contracts, basic digital integration can be coupled with BIM during the construction process. Given BIM's growing prevalence among professionals, large-scale road projects should position BIM alongside other basic digital integration tools, such as offline project management software. While software licensing costs may appear prohibitive, contracts of this nature provide parties with sufficient capacity to employ this method (CE 3). Basic digital tools remain essential to cement any technological progression sequence regardless of contract size or project type, with Construction Cloud and GIS mobile apps serving as the base, complemented by traditional methods.

RP 5 added that for projects of such a large scale, adopting 3D modelling as a feature of BIM can be positioned as basic due to its prevalence among Ghanaian firms. The main setback is likely resistance from traditional contractors who have operated with 2D drawings for decades without adopting BIM (RP 5). Nevertheless, since BIM has already gained prevalence among Ghanaian firms, coupling it with 3D modelling and framing it as an industry-standard expectation for large contracts normalises their adoption and reduces perceptions of these tools as disruptive innovations.

Theme 2 (consolidation phase): Digital Twins and IoT Networks for Localized Monitoring

This sequence represents a logical, cost-effective progression for contracts of this nature, with significantly reduced IoT sensor prices making laterite performance data integration advantageous for better understanding local soils compared to imported systems. According to a regulatory governing professional, digital twins could ease management stress through scenario planning and data-driven decision-making while maintaining quality standards (RP 6). While connectivity poses another significant challenge in remote areas, RP 6 mentioned that solar-powered cellular boosters and infrastructure-sharing partnerships with telecom companies could provide viable solutions. Participants further mentioned that the digital twin system would calibrate using both local laterite performance data and traditional vibration-based quality tests to ensure accuracy (CE4; LC3). The biggest long-term hurdle involves maintaining these systems without continuous foreign technical support, raising critical questions about standardisation and operational continuity. Building local capacity through technology transfer clauses in contracts and establishing maintenance partnerships with polytechnics would ensure the technological sequence remains viable and sustainable (CE 4).

Theme 3 (expansion phase): AI-optimized machinery routing

AI-optimised machinery must eventually be considered for projects of this nature, with its positioning at the end of the sequence appearing progressive. Although the technology is effective, investors must be convinced of implementation ROI, with achievement likely requiring more than three projects due to training costs (RP 5). Contracts of this size can handle this progression, with AI routing optimisation offering significant fuel cost reductions, although cultural aspects remain crucial. AI can develop scheduled quarry deliveries at night to avoid traffic, but as community rulers negotiate land access, requiring programming with consultation protocols to ensure technology adapts to social structures rather than conflicting with them is essential (LC 6). Participants further mentioned that, considering phased implementation across annual highway programmes rather than attempting everything simultaneously, ROI can be achieved after three projects (LC 6; CE 3).

5. DISCUSSION

5.1 Compatible HC4.0 (Digital-Traditional) Technologies for the Sub-Saharan Road Landscape

Aligning with the core tenet of HC4.0, the study identified six contextually viable digital-traditional technologies for Ghana's road infrastructure. Stakeholders emphasized BIM's value in streamlining design coordination, complemented by manual execution as a realistic HC4.0 technology due to its prevalence in industry circles, from anecdotal evidence. This hybrid model lowers over-engineering cost, enhances erosion resistance, and taps into the critique of BIM's unrealized potential in developing countries (Appiah, 2020). Similarly, Mobile Project Management Apps coupled with Manual Supervision emerged as a pragmatic hybrid technology response to the rural connectivity gaps that plague transportation construction in Ghana. With huge emphasis on their offline functionality, experts suggest their pertinence to enable real-time documentation while ensuring that this data can be later synced with central databases when connectivity is reached. By employing the ubiquitous mobile phones for process digitization without

replacing jobs, this blend operationalizes Maisiri et al. (2021) HC4.0 cost-minimisation strategy. Experts also lauded the viability of integrating low-cost IoT sensors in road subgrade materials such as gravel and laterite as a step to shifting to a predictive maintenance culture. Although the HC4.0 technology was notably mentioned, experts cautioned that the optimism of Edirisinghe (2019) is countered by pragmatic limitations such as durability in challenging climates, unreliable power, and rural connectivity. The phased adoption approach proposed in this study, such as the intermittent data syncing, resonates with Kissi et al.'s (2023) call for systematic integration frameworks. There was a notable mention of capitalizing on drone affordability to enhance survey accuracy in inaccessible terrains. By combining low-cost UAVs with traditional site surveys while integrating community knowledge of flood patterns and sacred lands, this HC4.0 technology increases efficiency while promoting sustainable stakeholder engagement. In the same vein, GIS & Satellite data coupled with Indigenous Land Use Knowledge bridges technical accuracy and community-oriented route optimization while promoting sustainable stakeholder engagement through participatory planning and ecological preservation. This hybrid model contributes to the effort of embedding community input into technical planning, a policy gap in Ghana's current landscape (Appiah, 2020). The study's last derived digital-traditional technology is the adoption of Modular Mobile Labs to enable on-field material testing, reducing delays from sample transportation while combining with on-site construction workflows. Irrespective of their feasibility in Ghanaian road infrastructure, stakeholders highlight the need for the lab designs to withstand Ghana's weather while enabling occupancy comfort. Table 5 displays the six hybrid methodologies identified to be compatible with Ghana's road infrastructure.

Table 5. Hybrid Methodologies compatible with Ghana's road infrastructure

HC4.0 Technology	Digital Component	Traditional Component	Key Benefits	Implementation Challenge
BIM + Local Construction Norms	BIM software (3D Modelling tools)	Manual Construction and local knowledge systems	Simulates local material performance, reduces over-engineering cost.	Software licensing cost, resistance from traditional contractors, and skill gap in BIM usage
Mobile Apps + Manual Supervision	Offline-capable project management apps, GIS apps, and WhatsApp Business	Face-to-face supervision and inspection	Real-time progress tracking, reduced travel costs, and maintains human oversight quality.	Rural connectivity limitations, device compatibility issues, and digital literacy requirements
IoT + Local Materials	Low-cost sensors, vibration monitoring, cellular data transmission	Laterite and gravel subgrades, manual emergency repairs, and visual inspection protocols	Shifts to predictive maintenance, real-time structural health monitoring, and cost-effective local material utilization	Sensor durability in a harsh climate, power supply reliability, and technical maintenance capacity
UAVs + Traditional Surveys	Low-cost drones, photogrammetry software	Ground surveys, community knowledge of flood patterns, and sacred land identification	Enhanced survey accuracy, reduced survey time and costs, access to difficult terrain, and community engagement integration	Weather dependency, regulatory compliance
GIS/Satellite data + Indigenous knowledge	GIS software, satellite imagery, low-bandwidth optimization	Community land use wisdom, flood patterns knowledge, and sacred site identification	Improved route optimization, enhanced community participation, early bottlenecks identification, and sustainable stakeholder engagement	Data accuracy translation, community participation, and technical specification integration
Modular Mobile Labs	Solar-powered digital testing equipment, tablets for data entry	On-site construction workflow, manual compaction tests	Immediate quality control eliminates sample transportation delays	Equipment durability requirements, occupancy comfort in harsh weather, and initial investment costs

Source: (Field Survey, 2025)

5.2 Viable Technology Progression Sequences for Contract Sizes

The analysis also identified technology progression sequences suitable for different contract sizes grounded in HC4.0's adaptive implementation theory by tailoring adoption to financial and technical capacity (Murguia et al., 2024). Road construction projects were categorized into three types based on their contract value.

For small-scale contracts typically valued less than 5 million cedis, the sequence encompasses two stages. The process begins with basic digital integration with tools such as Mobile GIS and WhatsApp Business. This foundational step supports proponents, emphasizing affordability and recommendations for leveraging ubiquitous technologies in resource-constrained settings (Maisiri et al., 2021). The second phase focuses on consolidating the foundation while including triggers for introducing Basic IoT Sensors and Rented UAV Photogrammetry, to enable erosion monitoring and real-time structural data without high upfront costs. Monthly UAV rentals circumvent capital lock-up, validating Maisiri et al. (2021)'s phased ROI approach, while orthodox labor maintains drainage using local flood knowledge.

For Medium-Scale Contracts, normally characterized by urban arterial roads and peri-urban highways within the threshold of GHS 5M–50M, stakeholders drew three stages in the progression chain. Phase 1 retains the basic digital tools integration recommended for small-scale contracts, but advances to Phase 2: BIM + IoT Moisture Sensors. The prevalence of BIM in Ghana supports clash detection and drainage modeling, and IoT sensors monitor laterite subgrades in real time during rainy seasons, preventing failure by adjusting gravel proportions based on real-time data. Phase 3 integrates Mobile Site Labs for on-field pothole prediction and material testing, eliminating delays in quality control and enabling lime-stabilized laterite adjustments. For medium-scale projects, the phased ROI buildup reflects Osunsanmi et al.'s (2018b) and Olatunde et al.'s (2022) selective digitalization, prioritizing high-impact, cost-effective tools.

Large-scale road projects are normally attributed to national highways and intercity corridors. For a project of this magnitude, stakeholders identified BIM as a baseline alongside basic digital integration tools with offline functionality. Phase 2 employs Digital Twins + IoT sensors for live structure monitoring, twin calibration against local laterite conditions, and traditional vibration tests. Experts affirmed that the affordability of sensors makes the hybrid model feasible, but stressed solar-powered solutions and local capacity building, such as polytechnic partnerships for sustainability. This sequence culminates with AI-Optimized Machinery Routing, reducing fuel costs via night deliveries but requiring community consultation to align AI with social structures. There was a wide consensus for ROI recoup after 3 projects by gradual adoption.

The patterns and progression sequences, as shown in Figures 1 to 3, operationalize diverse theoretical underpinnings. The hybridity at each phase bridges resource-limited compatibility gaps, aligning with Rogers' Diffusion of Innovations Theory (2003). Since the developments are centered on the economic conditions of Ghana, synonymous with Sub-Saharan African countries, these technological chains corroborate Technology Appropriateness Theory (Schumacher, 1973). The scalability of these progressions also requires policy support for technology transfer and maintenance partnerships, unaddressed barriers highlighted by Appiah (2020) and Kissi et al. (2023).

6. CONCLUSION

This investigation extends the current theoretical framework on the prospects of HC4.0 applications in the Sub-Saharan region, from the Ghanaian perspective. By hinging on synthesizing advanced construction technology practices with Ghana's workforce skilled in traditional construction methods, six contextually viable HC4.0 technologies were identified for Ghana's road infrastructure. These hybrid methodologies include BIM with manual execution, mobile project management apps coupled with manual supervision, integrating low-cost IoT sensors with locally sourced road subgrade materials, adopting UAVs with traditional site surveys while integrating community knowledge, GIS/Satellite data coupled with indigenous land use knowledge, and modular mobile labs to enable on-field material testing. The findings also derive viable technology progression sequences for different road contract sizes in Ghana.

From a practical standpoint, this study provides a structured model that enables construction firms to adopt digital technologies progressively while maintaining operational continuity. The integration of Building Information Modelling (BIM), low-cost Internet of Things (IoT) sensors, and mobile project management applications with manual supervision represents a cost-efficient route toward improved project delivery, enhanced quality assurance, and reduced wastage. The hybrid sequencing approach allows firms to realize measurable productivity gains without the prohibitive upfront investment associated with full digitalization. At the policy level, the study underscores the urgent need for institutional frameworks

that recognize hybridization as a legitimate modernization pathway rather than a temporary compromise. Such inclusion can stimulate digital transformation through incentive-based adoption strategies, targeted training programs, and technology-transfer partnerships between academia, industry, and government.

The research’s theoretical contribution advances the scholarly discourse on the role of emerging technologies in driving sustainability and circular economy practices in infrastructure development. The rapidly evolving nature of C4.0 technologies and, to some extent, C5.0 means some findings might face obsolescence as new technologies emerge. Although this limitation was curtailed by focusing heavily on hybrid integration principles rather than specific technology specifications, transferability is cautionary. While this study was situated within the Ghanaian road construction sector, the findings highlight hybrid pathways that may hold relevance for countries with similar infrastructural and institutional contexts across Sub-Saharan Africa. Nonetheless, caution is warranted in generalization. Variations in governance structures, economic conditions, regulatory environments, and resource bases mean that the proposed frameworks should be considered as transferable models rather than universally applicable solutions. Comparative studies across multiple Sub-Saharan countries are recommended to validate the scalability of the identified hybrid approaches. Furthermore, the empirical validation of this study’s proposed ROI timelines demands dedicated longitudinal inquiry. While expert-derived adoption sequences offer actionable guidance for small, medium, and large-scale contracts, their financial viability remains projected rather than proven. From this study, we can be informed about a whole new perspective of sustainable road construction in Ghana, positioning HC4.0 as a replicable blueprint for infrastructure modernization across the Global South.

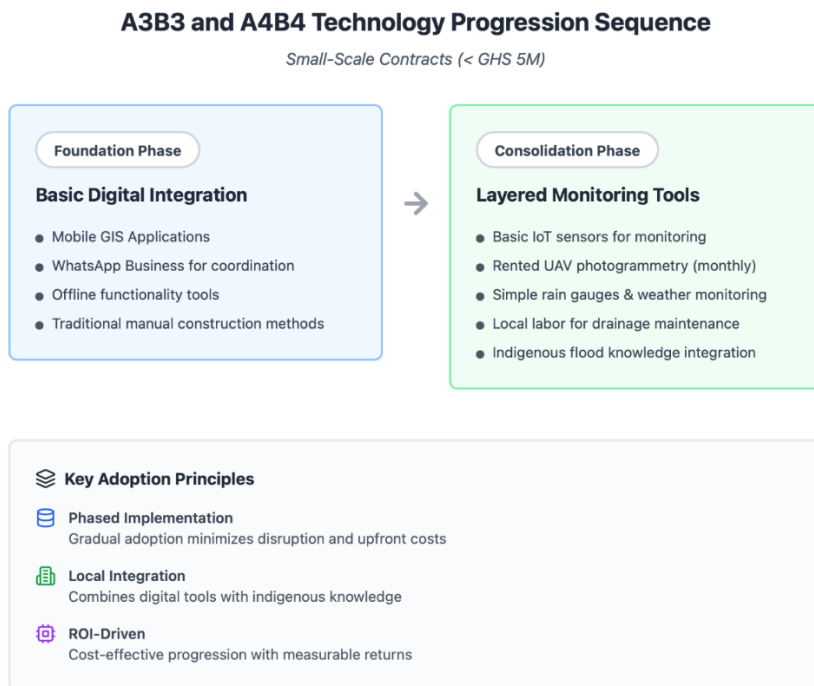


Figure 1. A3B3 and A4B4 Technology progression sequence
Source: (Field Survey, 2025)

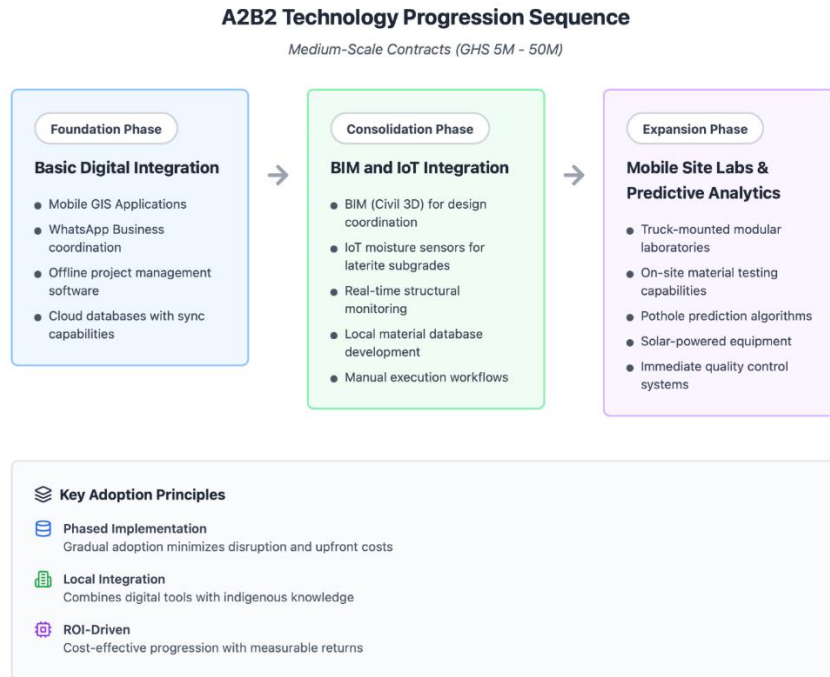


Figure 2. A2B2 Technology progression sequence
Source: (Field Survey, 2025)

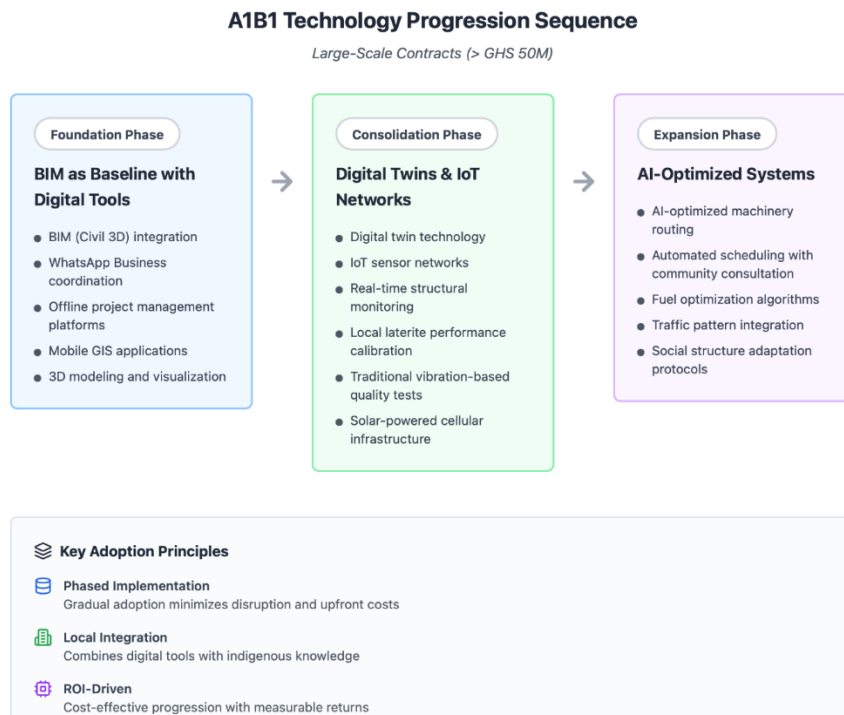


Figure 3. A1B1 Technology progression sequence
Source: (Field Survey, 2025)

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