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Assessment of the Adoption of Cyber-Physical Systems in the South African Construction Industry

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Abstract

The purpose of the study is to assess the adoption of cyber-physical systems in the South African construction landscape, as the construction sector undergoes a technological transition from traditional ways of doing things to enhance productivity. CPS integrates actual construction activities with innovative technologies, including sensors, automation, real-time data exchange, and intelligent control systems. Despite the evident benefits of CPS, adoption remains low, especially in developing countries like South Africa. The study adopted a mixed-methods research methodology. Firstly, a qualitative research methodology was adopted, and interviews were used to gather data, which were analyzed thematically. Secondly, for quantitative data, questionnaires were distributed and analyzed descriptively. The study found that key barriers to implementing CPS in the South African construction sector include high implementation costs, limited digital infrastructure, limited skills, resistance to change, and insufficient organizational support and policies. Furthermore, the study found that the drivers of CPS include leadership commitment, investment in digital skills, and improved technological infrastructure. The study enhances understanding of CPS in the South African construction landscape.

Keywords
Construction industry, Cyber-physical systems, Construction 4.0, Digital transformation, South Africa

1. Introduction
The construction sector, like many that require technological transitions due to productivity challenges, has still seen slow adoption of construction 4.0 technologies to mitigate these issues. Among these construction 4.0 technologies, CPS has attracted attention for integrating physical construction activities with innovative digital systems, including sensors, automation, real-time monitoring, and data exchange (You and Feng 2020). CPS enables collaboration among machinery, materials, workers, and digital platforms, enhancing data-informed decision-making and proactive project control. In developed countries, the adoption of CPS has been intertwined with smart construction practices, which improve construction execution performance and coordination throughout the project lifecycle (Oyediran et al. 2025).

As the construction sector has been hampered by time and cost overruns, low productivity, and uncoordinated communication, CPS provides solutions to these issues through more integrated, data-informed project execution.

In the South African construction sector, the adoption of CPS remains relatively low despite growing awareness of the digital technologies applicable to the sector (van Wyk et al. 2024). There is a vital need for transformation in the construction sector, as its productivity is very low due to a heavy reliance on traditional methods. There is also a lack of productivity growth, inadequate technological integration, and resistance to change from the traditional way of doing things to these innovative technologies (Meno 2020). In the broader construction agenda in the South African Construction sector, there has been steady awareness, but the extent to which CPS has been implemented and integrated into construction practices remains unclear (Singh 2025; Khafiso et al., 2025). Therefore, the objective of the study is to assess the adoption of cyber-physical systems (CPS) in the South African construction industry, providing insights into adoption levels, barriers to CPS adoption, and their contribution to digital transformation in the sector.

2. Literature Review

2.1 Concept of cyber-physical systems in the construction sector

CPS in the construction sector involves integrating construction processes with innovative technologies to enhance real-time monitoring, control, and optimization of project activities, especially during the execution phase. These systems consist of sensors, communication networks, and data analytics, combining hardware and software(Lee 2023). Thus, in practice, CPS is primarily aligned with construction 4.0 and comprises innovative technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), robotics, drones, and digital twins. By implementing these innovative technologies, the construction sector becomes more productive, less prone to issues, and more innovative. Through these smart environments, information is continuously collected from equipment, materials, and employees and used to support data-driven decision-making. Thus, this holistically enhances visibility across the project lifecycle, from design and planning through execution, close-out, and commissioning.

The actual application of CPS in the construction sector transcendentally enhances the project performance through automation, predictive analytics, and adaptive control processes. For instance, sensors integrated into construction machinery can help monitor machinery health and predict failures, while real-time data from IoT can enhance safety by identifying hazardous situations on construction sites. Furthermore, CPS enhances coordination among the stakeholders by ensuring that the project data is accurate, up-to-date, and accessible. Despite these evident benefits, the adoption of CPS in developing countries such as South Africa is constrained by persistent challenges, including inadequate digital infrastructure, high implementation costs, and a lack of skills (Khafiso et al. 2024). CPS is considered the main contributor to efficiency, productivity, and sustainability in the built environment sector, especially in construction site productivity.

3. Methods

The study employed a mixed-methods research methodology grounded in pragmatism, facilitating the integration of quantitative and qualitative approaches to thoroughly assess the adoption of cyber-physical systems in the South African Construction Industry. A concurrent triangulation strategy is utilized, employing structured questionnaires to gather quantitative data from construction professionals, including quantity surveyors, project managers, contractors, and architects, which is subsequently analyzed using descriptive statistics. Additionally, semi-structured interviews yield qualitative insights into stakeholders' experiences and perceptions of CPS adoption. Utilizing the research onion model, the study employs both deductive and inductive methodologies, integrating hypothesis testing with comprehensive contextual analysis. A case study methodology and a cross-sectional temporal framework are employed, utilizing data from both primary (questionnaires and interviews) and secondary (literature, industry reports, and government statistics) sources. The study employs purposive sampling to select knowledgeable participants, ensuring validity through triangulation and member checking, while maintaining reliability through standardized data collection procedures and adherence to ethical principles, including informed consent, confidentiality, and voluntary participation. Table 1 illustrates the demographic information of the respondents.

Table 1. demographic data of the respondents (source: Authors).

Participant	Rank/Firm	Years of Experience and Academic Qualifications	Codes
Client Representative	Clint Representative	Not below 10 years and a Bachelor's degree, respectively	CR1
Construction Project Manager	Consultant		CPM1
Quantity Surveyor			QS1
Architect			Arch1
Civil Engineer			CE1
Structural Engineer			SE1
Electrical Engineer			EE1
Mechanical Engineers			ME1
Construction Health and Safety Agent			CHSA1

4. Results and Discussion

Quantitative Findings

Findings in Table 2 indicate that various barriers prevent the adoption of CPS in the construction sector. High initial investment costs emerged as the leading barrier to CPS adoption in the South African construction sector, with a mean of 3.75, indicating strong consensus on this issue and suggesting that financial constraints are a key barrier to CPS implementation. This finding is consistent with the study conducted by Sawhney et al. (2020), which states that high initial costs are a key challenge to the adoption of advanced digital technologies, thereby discouraging adoption, especially in developing countries. Closest data security and privacy concerns, with a mean of 3.60, and inadequate digital infrastructure, with a mean of 3.66, also fall under moderate consensus among the respondents. These findings align with the study that argued that cybersecurity risks and infrastructural shortcomings are key barriers to construction 4.0 adoption (Pan& Zhang, 2021)

Furthermore, the lack of skilled personnel, with a mean of 3.22, indicates moderate consensus among construction professionals. This illustrates that the CPS's implementation primarily relies on skilled personnel; the absence of such personnel contributes to its limited adoption in the construction sector. Additionally, resistance to change and limited awareness also act as barriers to the adoption of CPs in the construction sector. His contrasts slightly with prior research, which often identifies cultural resistance and awareness gaps as major barriers in digital transformation (Vial, 2019; Li et al., 2018). The relatively higher standard deviations observed in some variables, particularly for data security concerns (SD = 2.17), suggest variability in respondents' perceptions, indicating differing levels of experience and exposure to CPS technologies.

Table 2. Barriers to the adoption of CPS in the construction sector

Barriers to the adoption of CPS in the construction sector	**1 = Near minor**	**2 = Minor**	**3 = Moderate**	**4 = Near major**	**5 = Major extent**	**Mean score**	**Standard deviation**	**Rank**
High initial investment cost	0	0	4	7	1	3.75	0.80	1
Inadequate digital infrastructure	0	2	7	2	0	3.66	0.6	4
Lack of skilled personnel	0	2	3	4	0	3.22	1.28	3
Resistance to change	1	2	0	0	0	2.66	0.52	6
Limited awareness of CPS benefits	1	5	4	0	0	2.3	2.63	5

Data security and privacy concerns	1	0	1	8	0	3.6	2.17	2

Qualitative findings

5.1 Theme 1: Barriers to the adoption of CPS in the construction Sector

The findings reveal strong convergence among respondents on the financial and technological barriers to adopting cyber-physical systems (CPS) in the construction sector. The Client Representative (CR1) emphasised the cost burden, stating that *"the initial investment required for CPS technologies is too high for many projects, especially when the return is not immediately clear,"* indicating a near-major level of agreement with quantitative findings where cost ranked highest. Similarly, the Construction Project Manager (CPM1) noted that *"without proper digital infrastructure and integration with existing systems, CPS implementation becomes impractical,"* highlighting infrastructural readiness as a key concern. These views are consistent with existing literature, which identifies high capital costs and inadequate infrastructure as primary barriers to digital transformation in construction (Oesterreich & Teuteberg, 2016; Sawhney et al., 2020). The alignment between respondents' perceptions and the literature demonstrates strong agreement, suggesting that financial and technological constraints remain dominant impediments, particularly in developing contexts such as South Africa.

In contrast, organisational and human-related barriers were discussed with a comparatively moderate level of agreement. For instance, professionals such as the Electrical Engineer (EE1) and Mechanical Engineer (ME1) pointed to skills shortages and data security concerns, which align with studies highlighting the need for specialized expertise and secure data environments in CPS adoption (Pan & Zhang, 2021). However, factors such as resistance to change and limited awareness were less emphasised by respondents, suggesting only a minor to moderate level of agreement, which somewhat contrasts with literature that often positions cultural resistance as a critical barrier (Vial, 2019; Li et al., 2018). This divergence implies that while human factors are relevant, they are not perceived as the primary constraints compared to economic and technological challenges.

5.2 Theme 2: Drivers to the adoption of CPS in the South African Construction Sector

The findings indicate that the adoption of cyber-physical systems (CPS) in the South African construction sector is largely driven by the need to enhance project performance and efficiency. Respondents emphasised that digital technologies enable improved coordination and faster project delivery, with the Construction Project Manager (CPM1) stating that "*CPS technologies allow us to monitor projects in real time, which significantly improves decision-making and reduces delays*," reflecting a high level of agreement with literature that identifies productivity and efficiency gains as primary drivers of digital transformation in construction (Sawhney et al., 2020; Oesterreich & Teuteberg, 2016). Similarly, client demand and competitive pressure were highlighted as key motivators, as firms are increasingly required to adopt advanced technologies to remain relevant in a competitive market. This aligns with studies suggesting that external pressures, including client expectations and industry competition, strongly influence the uptake of Construction 4.0 technologies (Li et al., 2018), indicating a strong convergence between empirical findings and existing research.

In addition, organizational readiness and strategic leadership emerged as critical drivers supporting CPS adoption. The Client Representative (CR1) noted that "*organizations with strong leadership and a clear digital strategy are more willing to invest in CPS technologies*," suggesting a moderate to high level of agreement with literature that highlights the role of leadership and organizational support in technology adoption (Vial, 2019; Pan & Zhang, 2021). Respondents also highlighted the importance of skills availability, safety improvements, and sustainability considerations, further reinforcing the value of CPS in modern construction practices. However, while these drivers are acknowledged, their influence appears slightly less pronounced than that of performance-related benefits, indicating a moderate level of agreement overall.

6. Conclusion

The study concludes that the adoption of cyber-physical systems (CPS) in the South African construction sector is influenced by a complex interplay of barriers and drivers, with financial and technological constraints emerging as the most significant impediments, while performance improvement, client demand, and strategic leadership act as key enablers. The findings reveal that although stakeholders recognize the potential of CPS to enhance efficiency, productivity, and decision-making, challenges such as high implementation costs, inadequate infrastructure, and skills shortages continue to limit widespread adoption. At the same time, the growing need for improved project delivery,

competitiveness, and sustainability is gradually driving the industry towards digital transformation. Overall, the study highlights the need for a coordinated approach that invests in digital infrastructure, builds capacity, supports policies, and fosters strong organizational commitment to accelerate the effective adoption of CPS within the South African construction sector.

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