DIGITAL SOLUTIONS FOR SUSTAINABLE CONSTRUCTION: EXPLORING AI'S ROLE IN ACHIEVING NET ZERO

Abdul Gafoor K A
Doctoral Scholar, S P Jain School of Global Management
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ABSTRACT

The construction sector is a leading contributor to global greenhouse gas emissions, accounting for substantial operational and embodied carbon. Addressing this environmental impact is fundamental to meeting net-zero goals. Recent developments in Artificial Intelligence (AI) offer new digital solutions capable of transforming sustainability performance across the entire project lifecycle. Yet, questions remain about how best to harness these technologies in a fragmented, risk-averse industry.

This conceptual study develops a lifecycle-based framework to explore how AI applications contribute to sustainable construction and decarbonisation. It integrates insights from global policy literature and scholarly research to examine AI's role in five key lifecycle phases: design, planning, execution, operations, and end-of-life. The study further incorporates the Technology–Organisation–Environment (TOE) framework and Dynamic Capabilities Theory (DCT) to investigate how contextual and organisational factors shape AI adoption. By aligning AI capabilities with net-zero goals, the framework advances a holistic view of digital sustainability in the built environment. The study also identifies key barriers—such as fragmented data ecosystems and insufficient digital governance—as well as enablers including lifecycle procurement models, smart policy incentives, and digital skills development. This paper contributes to the ISDSI-GLOBAL 2025 theme of "Tech for Net Zero" by presenting a theoretical foundation and practical pathway for AI-led sustainable construction.

Keywords: Artificial Intelligence, Net-Zero Construction, Sustainable Built Environment, Lifecycle Decarbonisation, Digital Twins, Circular Economy, Dynamic Capabilities, TOE Framework

INTRODUCTION

The global building and construction sector continues to play a central role in climate change, accounting for over 37% of energy-related CO_2 emissions and 34% of final energy use worldwide (GlobalABC, IEA, & UNEP, 2025). While energy efficiency in building operations has improved, emissions from construction processes and materials—also known as embodied carbon—have risen, reflecting the persistent gap between sectoral targets and on-ground transformation (Olawade et al., 2024).

The 2024/2025 Global Status Report highlights that only 10% of countries currently regulate whole-life carbon in buildings, while embodied emissions remain largely unregulated and underreported. The challenge is compounded by the construction industry's historically slow adoption of digital innovation (Liew et al., 2025), hindering decarbonisation and circularity.

Artificial Intelligence (AI) offers a unique opportunity to address this inertia. As an enabling digital technology, AI supports intelligent decision-making, predictive modelling, resource optimisation, and automation across complex workflows. While BIM and IoT have made inroads in construction, AI brings higher-order functions that may radically improve sustainability performance across the project lifecycle (Wang et al., 2024).

This paper explores the role of AI in enabling net-zero construction through a lifecycle-based framework that draws on two theoretical perspectives: the Technology–Organisation– Environment (TOE) framework and Dynamic Capabilities Theory (DCT). The study contributes a conceptual model that links AI-enabled digital transformation with sustainable construction outcomes.

LITERATURE REVIEW

Emissions and Lifecycle Complexity

The built environment is one of the largest global sources of CO_2 emissions, stemming from both operational energy use and the embodied carbon of materials and construction processes. As emphasised in the Global Status Report (GlobalABC et al., 2025), significant carbon reductions must occur across the entire lifecycle—design, construction, use, and decommissioning—if the sector is to align with 1.5°C climate targets.

Recent works emphasise the complexity of reducing embodied emissions, which continue to rise despite energy efficiency gains (Liew et al., 2025). Lifecycle-based strategies are increasingly promoted, encompassing circularity, digital material passports, and emissions transparency (Zuo et al., 2019). These approaches require digital enablers capable of capturing, analysing, and acting upon large, diverse datasets—an area where AI can add substantial value.

Emerging AI Applications in Construction

AI is being deployed in a growing range of applications throughout the construction lifecycle. In design, generative AI tools and optimisation algorithms help produce sustainable layouts with lower energy demand and reduced material waste (Marzouk & Othman, 2020; Olawade et al., 2024). During planning and scheduling, predictive analytics improve coordination and reduce resource inefficiencies (Wang et al., 2024).

Construction execution benefits from AI-driven robotics and site monitoring, reducing rework and emissions through enhanced safety and precision (Lu et al., 2019). Operational phases are supported by digital twins and smart control systems, enabling real-time feedback, adaptive building management, and energy forecasting (Mahamadu et al., 2018). At the end-of-life stage, AI aids in disassembly modelling, waste classification, and circular reuse strategies (Kouhestani et al., 2019).

Studies such as Liew et al. (2025) and Olawade et al. (2024) highlight how AI, when deployed holistically, can serve as a backbone for digital decarbonisation and sustainable construction ecosystems.

Barriers and Gaps in Adoption

Despite increasing use cases, several structural and technical barriers hinder

AI's widespread implementation in construction. Fragmented data environments, lack of interoperability between systems, and resistance to organisational change persist across many regions (Ding et al., 2019; Alreshidi et al., 2018). Additionally, there is limited empirical integration of AI applications within lifecycle sustainability frameworks, and few theoretical models explain adoption in the context of organisational capabilities and policy environments.

This gap motivates the development of a conceptual model linking AI technologies to lifecycle outcomes through the lenses of TOE and DCT.

THEORETICAL FRAMEWORK

Technology–Organisation–Environment (TOE) Framework

The Technology–Organisation–Environment (TOE) framework offers a structured lens through which to analyse how organisations adopt new technologies. In the construction context, technological factors include AI system maturity, integration with BIM platforms, and user- friendliness. Organisational factors involve leadership support, digital infrastructure, and internal skill sets (Saka & Chan, 2020). Environmental factors are influenced by regulatory pressure, client expectations, and incentives for digital sustainability (Liew et al., 2025).

The TOE framework thus allows for a contextualised understanding of AI readiness and adoption variance.

Dynamic Capabilities Theory (DCT)

Dynamic Capabilities Theory (Teece, 2007) focuses on a firm's ability to sense opportunities, seize them effectively, and transform its structures for sustained competitive advantage. Applied to construction sustainability:

- Sensing may involve identifying inefficiencies or carbon hotspots using data analytics.
- Seizing includes allocating investment to AI capabilities or engaging with green innovation networks.
- Transforming entails embedding digital practices into procurement, operations, and long-term strategy (Kumar & Tiwari, 2024).

Combining TOE and DCT offers a robust dual framework to explain how AI can be leveraged strategically in construction settings.

CONCEPTUAL FRAMEWORK DEVELOPMENT

This section presents a lifecycle-based conceptual framework that illustrates how AI can contribute to sustainable construction practices aligned with net-zero objectives. The framework is structured around five key project lifecycle phases—design, planning, execution, operations, and end-of-life—each mapped with corresponding AI applications and expected sustainability outcomes. It is underpinned by two guiding theoretical lenses: the Technology– Organisation–Environment (TOE) framework and Dynamic Capabilities Theory (DCT). The rationale for using a lifecycle approach stems from the understanding that emissions reduction and resource optimisation must occur at multiple stages of the built environment— not merely during operations. By structuring the framework around the project lifecycle, the model encourages integrated thinking across traditionally siloed phases, while also allowing specific interventions to be tailored to each stage. AI tools serve as enablers within this framework, providing data-driven insights, adaptive control, and predictive analytics. Each phase reflects both technical applications and the organisational or environmental contexts necessary for implementation, as described through TOE and DCT dimensions

Table 1

Project Phase	AI Application	Sustainability Contributions
Design	Generative design algorithms, embodied carbon modelling	Material efficiency, passive energy optimisation
Planning	Predictive logistics, carbon-aware scheduling	Efficient resource allocation, emission forecasting
Execution	AI-assisted robotics, safety analytics, site monitoring	Reduced rework, lower on-site emissions, safer operations
Operations	Digital twins, adaptive controls, fault diagnostics	Real-time energy optimisation, HVAC efficiency
End-of-Life	Disassembly modelling, AI-based traceability	Circularity, reuse potential, waste minimisation

This model reflects insights from both recent empirical studies (e.g., Olawade et al., 2024; Wang et al., 2024) and policy guidance (GlobalABC et al., 2025).

Informed by the TOE framework, technological readiness (e.g. AI maturity, BIM integration), organisational capacity (e.g. leadership, skills), and external influences (e.g. regulation, stakeholder pressure) each act as moderators shaping the success of AI interventions across these phases. For instance, generative design tools require both software compatibility (technology) and supportive design culture (organisation), while

digital twin deployment depends on client demand for performance-based outcomes (environment).

Dynamic Capabilities Theory further clarifies how firms can evolve to embrace these tools. The capability to **sense** inefficiencies (e.g. carbon hotspots), **seize** opportunities (e.g. through digital procurement), and **transform** internal systems (e.g. embedding AI in standard workflows) is critical to actualising sustainability benefits. For example, end-of-life disassembly analytics are only effective when firms have developed the capacity to trace materials and align reuse strategies with long-term asset planning.

This integrated framework contributes to both theory and practice. Theoretically, it bridges technical applications with organisational adaptability, offering a dynamic, systems-level view of digital sustainability. Practically, it serves as a roadmap for construction firms and policymakers seeking to embed AI across the lifecycle in pursuit of net-zero performance.

DISCUSSION AND IMPLICATIONS

The proposed framework offers both theoretical and practical insights.
From a theoretical standpoint, it reinforces the need to view AI not merely as a technology, but as a system-level enabler of dynamic capabilities. It also bridges gaps between AI functionality and strategic sustainability alignment—an area under-explored in the construction literature (Pan & Zhang, 2021).

Practically, organisations can use the model to identify digital readiness gaps, prioritise lifecycle-oriented AI investments, and coordinate sustainability goals with procurement and project management functions. As demonstrated by Liew et al. (2025), such alignment can accelerate decarbonisation across multiple built environment stakeholders.

For policymakers, the framework suggests key levers to enhance AI uptake: performance-based regulations, data interoperability standards, and funding for digital infrastructure in public projects. These tools are critical to mainstreaming AI as a climate solution..

Future Research Directions

Future work should:

- Test the framework in empirical settings across project types and geographies.
- Develop AI readiness assessment tools based on TOE and DCT.
- Integrate edge-AI, blockchain, and sensor fusion technologies for enhanced real-time decarbonization.
- Investigate ethical implications of AI in construction, including transparency, job displacement, and accountability.

CONCLUSION

AI has the potential to serve as a keystone in the digital transformation of sustainable construction. By enabling lifecycle optimisation, reducing carbon emissions, and improving decision-making, AI offers tangible pathways to net-zero targets.

This paper presents a novel conceptual framework grounded in lifecycle analysis and strategic management theory, clarifying how AI can be adopted and scaled across the built environment. It contributes to both scholarly discourse and practitioner strategy at a time when digital innovation is critical to climate resilience in the construction sector.

REFERENCES

- Alaloul, W. S., Liew, M. S., Zawawi, N. A. W. A., & Mohammed, B. S. (2020). Industry 4.0 in the construction industry: Challenges and opportunities for sustainable development. Automation in Construction, 119, 103312.
- Alreshidi, E., Mourshed, M., & Rezgui, Y. (2018). Factors for effective BIM governance. Automation in Construction, 96, 1–11. https://doi.org/10.1016/j.autcon.2018.08.003
- Ding, Z., Liu, H., Hu, Y., & Zhou, Y. (2019). A comprehensive framework for BIM and sustainability integration in construction. Automation in

Construction, 107, 102935.

- Garcés-Ayerbe, C., Rivera-Torres, P., Suárez-Perales, I., & Leyva-de la Hiz, D. I. (2019). Is it possible to change from a linear to a circular economy? An overview of opportunities and barriers for European SMEs. International Journal of Environmental Research and Public Health, 16(5), 851.
- GlobalABC, IEA, & UNEP. (2025). Global status report for buildings and construction 2024/2025: Not just another brick in the wall – The solutions exist. United Nations Environment Programme.
- Kouhestani, M., Heidari, S., & Mahdavinejad, M. (2019). Framework for energy- efficient construction based on lean and BIM integration. Applied Energy, 248, 366– 379.
- Liew, M. S., Alaloul, W. S., & Shuang, Y. (2025). Digitalisation of construction: A pathway to decarbonisation and circularity. Next Sustainability, 5, 100050.
- Lu, Q., Xie, X., & Wu, Y. (2019). Smart construction: A new approach to improve productivity and sustainability in construction. Journal of Construction Engineering and Management, 145(2), 04018143.
- Mahamadu, A.-M., Mahdjoubi, L., & Booth, C. A. (2018). Digital twin applications in construction: A systematic review. Automation in Construction, 93, 273–284.
- Marzouk, M., & Othman, A. (2020). BIM-based optimisation for green building design. Automation in Construction, 103, 102970.
- Olawade, D. B., Wada, O. Z., David-Olawade, A. C., Fapohunda, O., Ige, A. O., & Ling, J. (2024). Artificial intelligence potential for net zero sustainability: Current evidence and prospects. Next Sustainability, 4, 100041.
- Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. Automation in Construction, 122, 103517.
- Saka, A. B., & Chan, D. W. M. (2020). Adoption of digital technologies in construction: Barriers and strategies. Journal of Building Engineering, 32, 101722.
- Teece, D. J. (2007). Explicating dynamic capabilities: The nature and microfoundations of sustainable enterprise performance. Strategic Management Journal, 28(13), 1319–1350.
- Tornatzky, L. G., & Fleischer, M. (1990). The processes of technological innovation. Lexington Books.
- Wang, Y., Wang, X., Wang, J., & Yung, P. (2024). AI-integrated digital twins for real-time carbon monitoring in smart buildings. Buildings, 14(2), 2752.
- Zuo, J., Zhao, Z., & Wu, W. (2019). Mapping the landscape of sustainable construction: A bibliometric review. Renewable and Sustainable Energy Reviews, 103, 123–132.