CONSTRUCTION ORGANISATION MANAGEMENT MODEL FOR DIGITAL TWIN IMPLEMENTATION TO REDUCE OPERATIONAL CARBON IN BUILDINGS

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Abstract
The fragmented nature of Digital Twin (DT), multidisciplinary involvement, and overarching carbon criteria pose challenges for construction organisations' management in effectively implementing DT for reducing operational carbon (ROC) in buildings. However, a critical research gap exists in how effective management can enhance DT adoption within the context of construction organisations. This study aims to develop a Construction Organisation Management-Model (COM) to enhance DT adoption among construction firms towards reducing operational carbon emissions in existing buildings. Questionnaire data from 345 multidisciplinary construction experts across the globe were analysed via confirmatory factor analysis. As a result, the structural model was developed. Specifically, the combined implementation of key elements like technology adoption, process reengineering, change management, and complex system interconnections positively impacts the management of DT for ROC. Performance monitoring & evaluation play a critical intermediary role between the abovementioned elements and the management of DT for ROC, while government & stakeholder involvement mediates solely between technology adoption and the effective management of DT for ROC. The study demonstrates how various management theories interconnect to facilitate the adoption of complex emerging technologies such as DT while presenting an actionable pathway for construction organisations to reduce carbon emissions in existing buildings.

Keywords: Construction Management, Digital Twin, Operational Carbon, Buildings, Retrofitting.

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INTRODUCTION

Operational emissions, attributed to the energy required for heating, cooling, and day-to-day operations, constitute 70% of the building sector's carbon footprint (Ohueri et al., 2023). Consequently, construction organizations are increasingly embracing digital innovations like digital twin (DT) technology in retrofitting practices, given its substantial potential to reduce operational carbon emissions by over 40% (Yu et al., 2022; PBC, 2023). For instance, DT technology enhances HVAC systems with real-time sensor data, enabling predictive maintenance and energy-efficient settings (Shen and Li, 2024). It engages occupants with energy-usage feedback, supports building analysis, indoor air quality management, and renewable energy integration (Alnaser et al., 2024). Additionally, DT enables data-driven decision-making and carbon tracking (Ohueri et al., 92023). However, DT presents a multifaceted system involving the creation of a digital representation of physical entities bolstered by the Internet of Things (IoT) – a network of interconnected devices equipped with sensors, actuators, and software (Ma et al., 2023). This complexity is exacerbated by the participation of multidisciplinary stakeholders and the exchange of extensive data, including overarching carbon criteria, among various applications (Celis-D'Amico et al., 2023).

Hence, the adoption of DT in construction firms remains relatively low, estimated at only 10-20%, significantly lagging the manufacturing sector, which has achieved approximately 70% adoption (de Wilde, 2023; Ohueri et al., 2023). This disparity undermines the construction firms' ability to fulfil the United Nations mandate of leveraging digital technology to reduce operational carbon emissions by over 6 gigatons. What is more intriguing is that the literature on DT in construction has predominantly focused on identifying strategies and challenges (Oke et al., 2023; Bortolini, 2022; Tahmasebinia et al., 2023), with a substantial portion emphasising the technological aspect of DT (Francisco et al., 2020; de Wilde, 2023; Hasan et al., 2022; Arsiwala et al., 2023). Other studies have primarily investigated trends and state-of-the-art reviews (Lucchi, 2023; Shen, 2024), while some have focused on developing generic frameworks for DT adoption (Piras et al., 2024; Kang et al., 2024).

The crucial management aspect essential for enhancing DT implementation within construction firms, particularly in effectively managing the inherent complexities of DT systems to promote its adoption in the construction sector, is largely overlooked in existing literature (Bunjaridh et al., 2023). Despite the existence of numerous management theories, there is a lack of studies addressing how these theories can be effectively adapted, combined, and implemented within construction firms to enhance the adoption of emerging technologies (Ozumba et al., 2019), like DT, particularly for building retrofitting practices. The role of management in facilitating technology implementation in construction organisations cannot be underemphasized. Hence, a need for further investigation in this domain is paramount. This study aims to develop the construction organisation management model (COM) to drive the adoption of DT among construction organisations while simultaneously reducing carbon emissions in operating buildings.

The research findings will advance efforts in adopting digital technology to mitigate carbon emissions, thereby contributing to climate change mitigation efforts. This investigation into the development of COM is guided by the flow chart below.

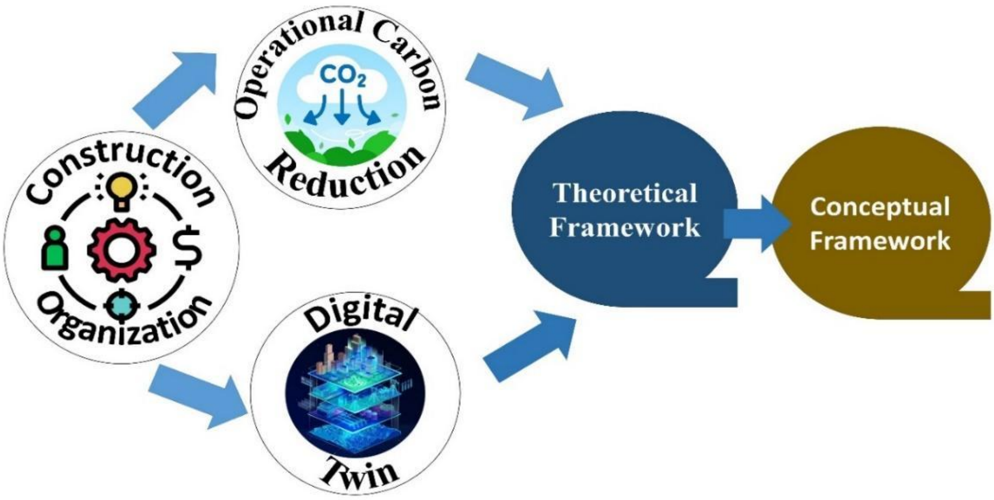

Figure 1: COM Investigation Process Flow

COMPLEXITIES OF MANAGING DT FOR ROC WITHIN THE CONSTRUCTION ORGANISATION

Jiang et al. (2021) posited that implementing DT by construction organizations to reduce carbon emissions in operating buildings remains a complex task. Hence, Tao et al. (2029) identified five major components of DT implementation, as shown in Figure 2.

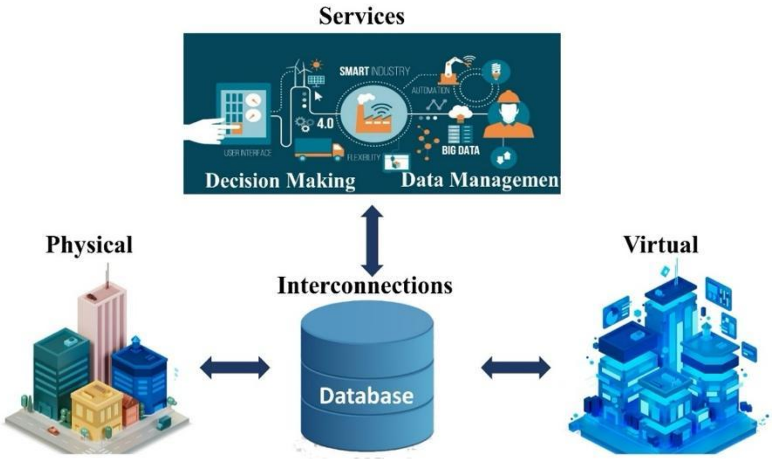

Figure 2: The 5 Multifaceted Digital Twin Components

Figure 2 shows that DT implementation consists of the physical part: the main component. Then, the virtual part replicates the physical part. The interconnection allows for the transfer of data, while services include physical monitoring of objects, simulations, and decision-making. Finally, the database enhances the system's convenience, productivity, and reliability.

The multifaceted DT system, compounded by the multidisciplinary expertise and cumbersome carbon criteria for enormous building components such as HVAC systems, insulations, building envelope materials, and lighting systems (Huang., 2024), makes it difficult for construction organizations to adequately implement DT to reduce carbon emissions in operating buildings. The relationship between DT technology, carbon reduction criteria, and construction organization is shown in Figure 3.

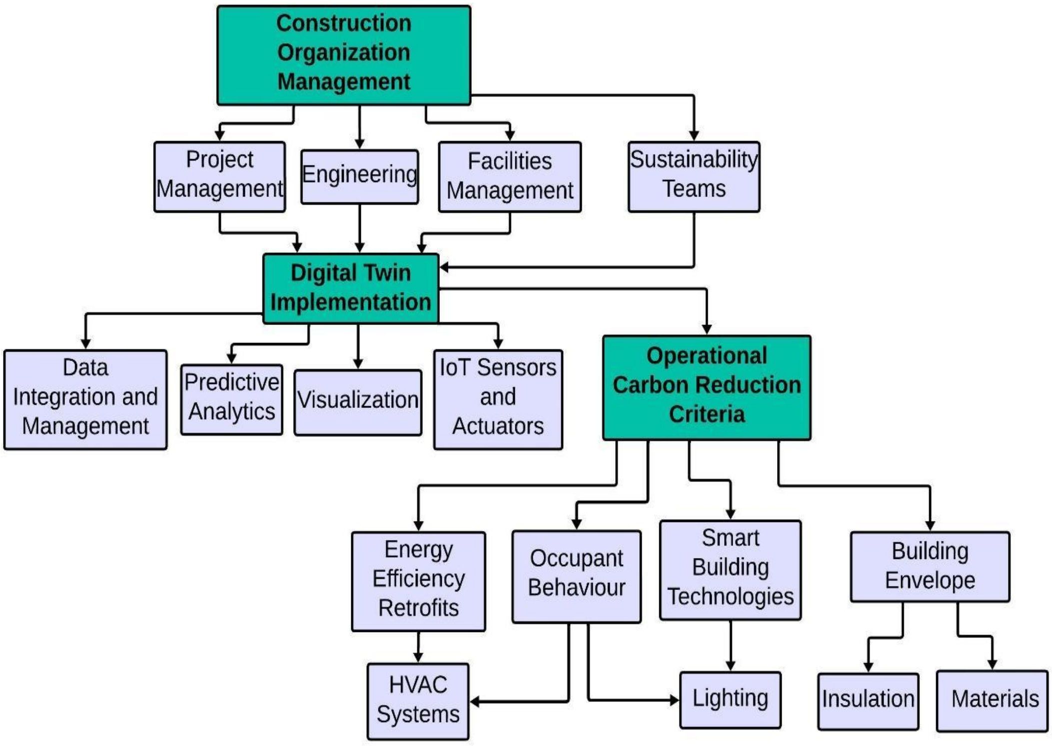

Figure 3: Complexity of Construction Organisations' Management of DT for ROC

Integrating these three different and fragmented components comes with several challenges, including interoperability issues. This is compounded by inadequate technical expertise and inadequate incentives (Botín-Sanabria et al., 2020). The consequence is inaccurate data analysis, unreliable decision-making process, and persistent reluctance to adopt DT for building retrofitting (Celis-D'Amico et al., 2023). This is among the major causes of the steady rise in operational carbon emission, which increased by 4% in 2022, and the low adoption rate of DT, which stood at a mere 20% in 2022 (UNEP, 2023; PBC, 2023).

Research Gap

To understand the increasing research on DT for building retrofitting in the construction sector and assess research gaps, VOSviewer software was used for scientometric mapping. Wen et al. (2021) and Omrany et al. (2022) highlighted VOSviewer's pivotal role in visually representing the research landscape, mapping keyword relationships, and quantifying research gaps. This is illustrated in Figure 4.

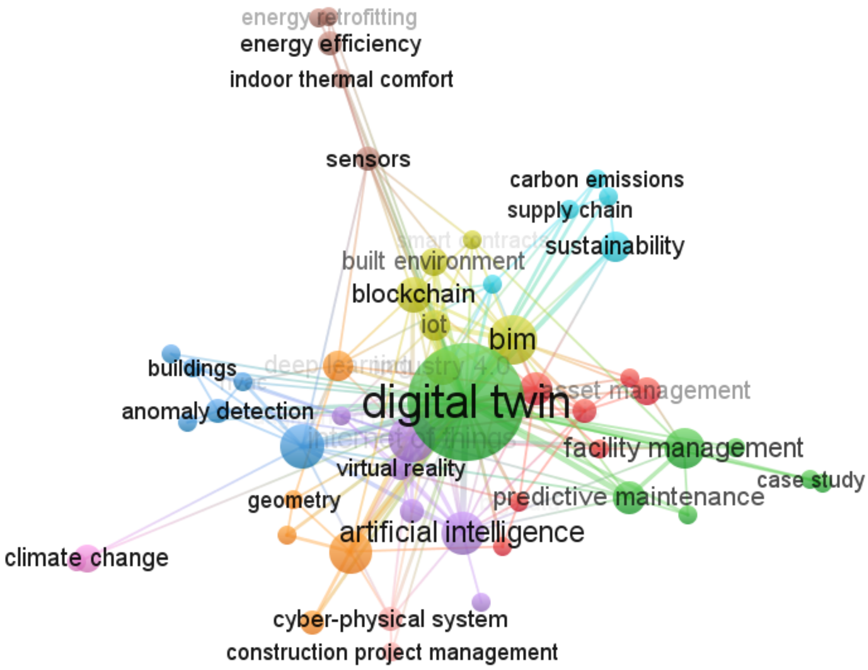

Figure 4: Co-occurrence Analysis of Keywords

Figure 4 shows the trajectory of DT research in construction context within the last 5 years (2018 to 2023). The size of the circle in the figure represents the frequency of occurrences of the keywords while the thickness of the line represents the number of times the terms are connected. The research trajectory is further interpreted in Table 1 to show the actual number of times these keywords occurred.

Table 1: List of co-occurrences for author keywords of DT for ROC

Keywords	**Occurrences**	**Total Link Strength**
Digital Twin	140	250
Building Information Modelling (BIM)	41	69
Internet of Things (IoT)	30	60
Artificial Intelligence	26	58
Machine Learning	20	55
Industry 4.0	18	50
Blockchain	14	47
Virtual Reality	12	40
Cyber-Physical System	10	34
Supply Chain	8	29
Energy Efficiency	7	24
Indoor Thermal Comfort	4	18
Predictive Maintenance	3	11
Facility Management	3	7
Carbon Emissions	2	3
Construction Project Management		

As highlighted in Table 1, DT emerges as the central keyword, dominating the scholarly discourse with a substantial occurrence of 140. This reflects the extensive attention this transformative concept has garnered within the research community. However, carbon emissions stand in stark contrast with its meager occurrence of just 3, highlighting the scarcity of research in this area, as affirmed by Wang et al. (2023). In addition, only a single occurrence was identified for the management of DT in building retrofitting within the context of construction organizations. To further comprehend the mapping results, qualitative exploration of the research was conducted.

The literature on construction organization implementation of DT in building retrofitting practices focuses on four main research streams. Firstly, studies by Piras et al. (2024) and Kang et al. (2024) focus on developing generic frameworks, lacking detailed information on the management aspect of DT in retrofitting. Secondly, Oke et al. (2023), Bortolini (2022), and Tahmasebinia et al. (2023) investigated strategies and challenges of DT application in the building sector. Thirdly, Francisco et al. (2020), de Wilde (2023), and Hasan et al. (2022) explore the potential of various DT systems, such as ML, IoT, and AI, in driving retrofitting practices in existing buildings. Fourthly, Piras et al. (2024); Kang et al. (2024) developed generic frameworks for DT adoption.

The potential to significantly enhance the adoption of emerging technologies in the construction sector is hindered by a critical management aspect largely overlooked in the existing literature (Maali et al., 2020). As emphasized in CIDB (2022) report, there is a significant gap between technology development's value and its effective implementation. Furthermore, the United Nations Technology and Innovation Report 2021 highlights that organizations' management faces serious challenges in introducing technology due to a lack of a proper management approach. Nnaji et al. (2023), among many authors, have proven that management theories drive technology adoption in organizations. However, Fréry (2023) suggests that technological advancements, including digital platforms and generative artificial intelligence, challenge established management theories, highlighting the necessity of integrating these theories to tackle the complexities of contemporary technology.

Jöhnk et al. (2022), Bunjaridh et al. (2023), and Stojanovic et al. (2021) stressed the need for robust and dynamic management approaches that align with the organization's overall objectives. The aim of this study is to develop a Construction Organization Management-Model (COM) to enhance DT adoption among construction firms while concurrently reducing operational carbon emissions in existing buildings. This is achieved by integrating six theories and adapting them to address the intricacies of the construction sector, digital technologies, and the human aspect. By incorporating key elements from these theories, a unified approach for managing DT in the context of carbon emission reduction is proposed, offering a practical solution to address the challenges associated with amalgamating multiple theories.

CONSTRUCTION ORGANISATIONS' MANAGEMENT OF DT IN ROC: BEYOND THE STATE OF THE ART

To effectively navigate changing markets, compete, and discover new avenues for value generation, a strong management plan is essential (Dastane 2020). This research's theoretical underpinnings are based on six well-known management theories that are essential for furthering the study of new technology adoption and dynamic environmental problems. The included theories are the Technology Acceptance Model (TAM), Business Process Reengineering (BPR), Systems Theory, Balanced Scorecard, Prosci's ADKAR (Awareness, Desire, Knowledge, Ability, and Reinforcement) Model, and Stakeholder Theory.

In the context of construction organisation management, **TAM** provides a structured framework for thoroughly evaluating stakeholders' perspectives and attitudes toward adopting advanced technologies (Na et al., 2022); including DT technology to reduce operational carbon emissions in buildings. Additionally, it facilitates identifying potential obstacles and customising implementation strategies to enhance acceptance and utilisation. **Business Process Reengineering (BPR)** supplements this approach by proposing a strategic management methodology for organizations, including construction, to redesign and optimize existing workflows and processes (Dagher and Fayad, 2024), thereby leveraging DT technology to effectively reduce operational carbon emissions in existing buildings.

Prosci's ADKAR Model offers an organised approach to managing individual and organisational change by focusing on Awareness, Desire, Knowledge, Ability, and Reinforcement (Prosci, 2024). Leung et al. (2021) have argued that integrating the ADKAR Model in construction firms can effectively overcome the resistance to change by guiding stakeholders through the change process and nurturing successful implementation and utilisation of emerging technologies. According to Gong et al. (2023), **Systems Theory** is an interdisciplinary field that studies the behaviour of complex systems, emphasising their interrelated components and interactions. Given the intricate nature of construction organisations, DT systems, and overarching carbon criteria, Systems Theory offers a holistic framework for comprehending the interconnections and interactions among diverse components within complex systems (Geng et al., 2021).

The **Balanced Scorecard** is a strategic performance management tool that enables organisations to evaluate their performance (Torgautov et al., 2022). In the context of construction organization management, especially in implementing DT technology for reducing operational carbon emissions in buildings, the Balanced Scorecard offers a comprehensive framework for assessing the effectiveness of carbon reduction initiatives. It helps construction firms identify improvement areas and make data-driven decisions to optimise DT implementation (Gunduz and Al-Naimi, 2022). **Stakeholder Theory** guides the engagement and collaboration with various stakeholders, including government agencies, regulatory bodies, industry partners, and building occupants, in organisational decision-making processes (Wojewnik-Filipkowska et al., 2021; Beck and Storopoli, 2021).

Inculcating these theories into construction organisation management strategies provides a holistic approach to addressing the complexities of adapting DT in reducing operational carbon emissions. The relationships of the theories are illustrated in Figure 5.

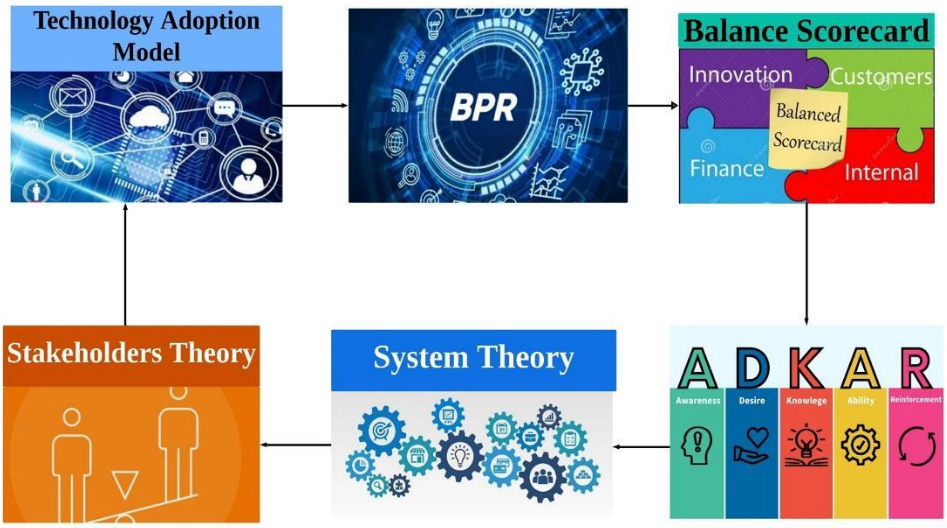

Figure 5: Theoretical Framework

This fusion, illustrated in Figure 5, is imperative as it equips practitioners with a comprehensive roadmap to navigate various challenges to ensure the effective utilisation of digital technologies in practice. The idea behind the concept is the Project Management Book of Knowledge (PMBOK) assertion that the construction organisation ought to draw from various concepts to effectively manage complex scenarios.

Elements of Construction Organisation Management of DT in ROC

Identifying the elements and sub-elements of the adapted management theories is a critical aspect of this study and constitutes the novelty of this study, considering that this innovation has not been explored cohesively in current literature. Table 3 below shows the elements and sub-elements drawn from fragmented studies in management theories and construction organisation implementation of technology to enhance sustainability practices.

Table 2: Elements of Construction Organisation Management of Digital Twin in Reducing Operational Carbon in Buildings

Technology Adoption (TA)																				
TA1	**Assessing Perceived Usefulness** of Digital Twin for Carbon Reduction		●				●													
TA2	**Evaluating Perceived Ease of Use** of Digital Twin for Carbon Reduction						●													
TA3	Compatibility with Existing Processes and Systems		●				●									●				
TA4	Perceived Relative Advantage over Traditional Methods		●				●									●				
TA5	**Demonstration of Tangible Benefits** in Carbon Emission Reduction		●				●									●				
Process Reengineering (PR)																				
PR1	**Conduct** Carbon Emission **Analysis**														●				●	
PR2	**Carry out** DT Integration **Assessment**													●	●				●	
PR3	**Process Redesign** for Carbon Reduction													●					●	
PR4	Establish Data Management Framework													●	●					
PR5	Performance Monitoring Mechanism													●	●					
Change Management (CM)																				
CM1	Change Readiness Assessment	●		●																
CM2	Communication Plan Development	●																		
CM3	Resistance Management Strategies			●														●		
CM4	**Cultivation of a Culture of** Carbon Reduction																	●		
CM5	Continuous Improvement Mechanisms			●														●		
Complex System Interconnections (CSI)																				
CSI1	System Boundary Definition				●			●												
CSI2	Development of Interoperability Protocols							●												
CSI3	Identify Data Exchange Mechanisms for Seamless Integration									●										
CSI4	Complex System Integration Strategies				●			●		●										
CSI5	Resilience Assessment				●			●												
Performance Monitoring & Evaluation (PME)																				

PME1	Select Key Performance Indicators (KPIs) for Carbon Footprint Reduction					●					●									
PME2	**Implement Protocols** for using DT based technology Carbon Emission Metrics					●					●									
PME3	**Assurance of Data Quality** for Carbon-Related Data					●			●											
PME4	**Utilization of Data Analysis Techniques** for Carbon Insights Carbon Impact Predictions								●											
PME5	Establishment of Continuous Improvement Feedback Loops					●					●									
Government & Stakeholders Involvement (GSI)																				
GSI1	Engagement with Regulatory Bodies for Compliance											●					●			
GSI2	Collaboration with Government Agencies for Support											●					●			
GSI3	Involvement of Industry Partners for Knowledge Sharing											●								
GSI4	Engagement with Building Occupants for Feedback											●	●							
GSI5	Alignment with Sustainable Development Goals (SDGs)												●							
Construction Organisation Management-Model (COM)																				
COM1	Redesigning operations for digital twin integration and carbon reduction													●						
COM2	Facilitating smooth transitions for digital twin adoption									●										
COM3	Ensuring seamless integration of digital twin systems																			●
COM4	Continuous assessment of digital twin performance for carbon reduction																			●
COM5	Engaging stakeholders for regulatory compliance and support																			●

Table 3 is supported by a conceptual combination (CM). CM refers to the cognitive process through which two or more concepts are merged to create a new conceptual entity that cannot be adequately described by a single concept alone (Ran and Duimering, 2010). The studies referenced in Table 2 provided generic sub-elements from 6 theories, which were then adapted and tailored explicitly to the context of this study. These elements and sub-elements form the theoretical foundation for developing a robust construction organisation model to manage DT in ROC effectively. Rather than extensively analysing each theory, this study utilises their relevant ideologies and concepts to navigate the complex landscape of construction organisations, diverse DT systems, and overarching carbon criteria. According to Pieters et al. (2021); Fuhrmann (2019), merging multiple theoretical approaches enables the management team to capture the complexities inherent in the construction organization. This facilitates a holistic understanding and enhances strategic implementation and decision-making in construction organisation management (Tayal et al., 2024). Leveraging the identified elements rooted in six theories, this study develops a conceptual framework to guide the realisation of the research aim.

CONCEPTUAL FRAMEWORK DEVELOPMENT AND HYPOTHESES

A conceptual framework serves as a visual or written representation of the key concepts, variables, and their interrelationships within the research (Ohueri, 2022). In the context of this study, the conceptual framework consists of the fundamental elements that facilitate the construction organisation's implementation of DT for ROC. To be measurable, the elements, now referred to as variables, are reduced from their level of abstraction and operationalised, constituting the independent, mediating, and dependent variables of the conceptual model. As viewed by Sekaran and Bougie (2014), variables differ at various times for the same object or person or at the same time for different objects or persons. The conceptual framework is shown in Figure 6.

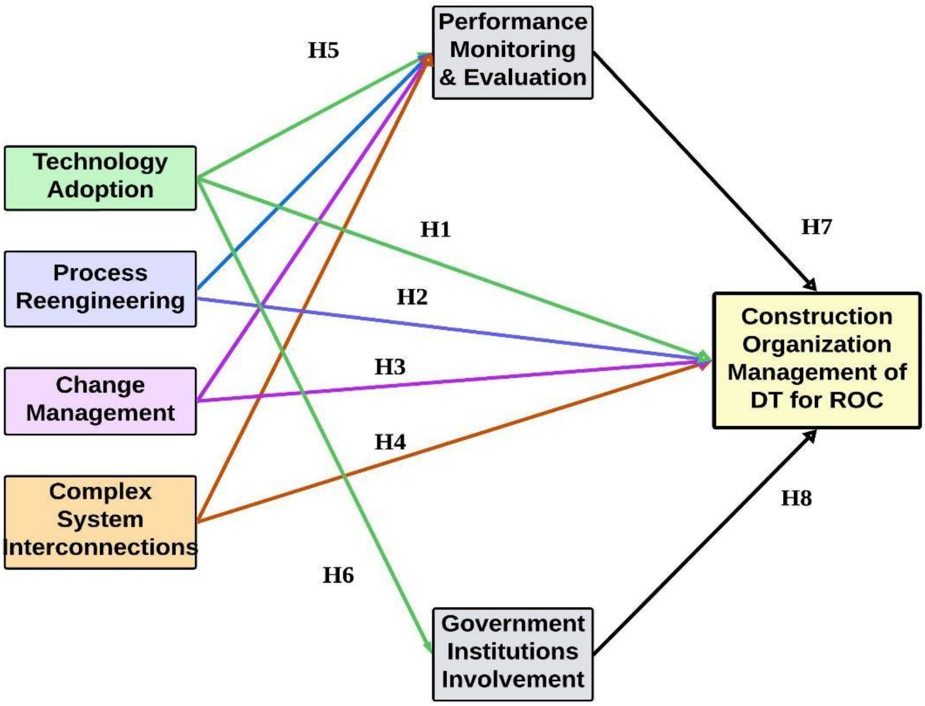

Figure 6: Conceptual Framework

The conceptual framework in Figure 6 highlights the key elements that are pivotal for managing DT in construction organisations to reduce operational carbon in building retrofitting. The independent variables include Technology Adoption (TA), Process Reengineering (PR), Change Management (CM), and Complex System Interconnections (CSI). Performance Monitoring & Evaluation (PME) and Government & Stakeholders Involvement (GSI) are mediating variables. The dependent variable is Construction Organisation Management of DT for ROC. By harmonising these elements, the construction organisation optimises DT management, ensuring efficient adoption of the complex DT systems to effectively reduce operational carbon emissions in the existing buildings. (Refer to Table 3 for the research hypotheses).

RESEARCH METHODOLOGY

This study employed a comprehensive approach, integrating critical literature review, bibliometric mapping, and quantitative research methods to achieve the research aim. Through meticulous selection criteria of inclusive and exclusive, a robust literature review was conducted to delineate the current state of construction organisation management of DT for ROC. Utilising VOS Viewer, the research trajectory was mapped, and the knowledge gap was quantified, providing a quantitative assessment of existing literature. This was complemented by a qualitative exploration involving a critical review of existing studies, in line with the approach advocated by Aziminezhad and Taherkhani (2023), to further elucidate the research gap and justify the necessity of this study. Moving beyond the state of the art, a theoretical framework, key elements, and a conceptual framework were established to guide the quantitative research method. Subsequently, a questionnaire survey was used to gather insights from a diverse group of 345 multidisciplinary experts, effectively bridging theoretical concepts with practical applications. The methodological framework is visually represented in Figure 7, providing a clear overview of the research approach.

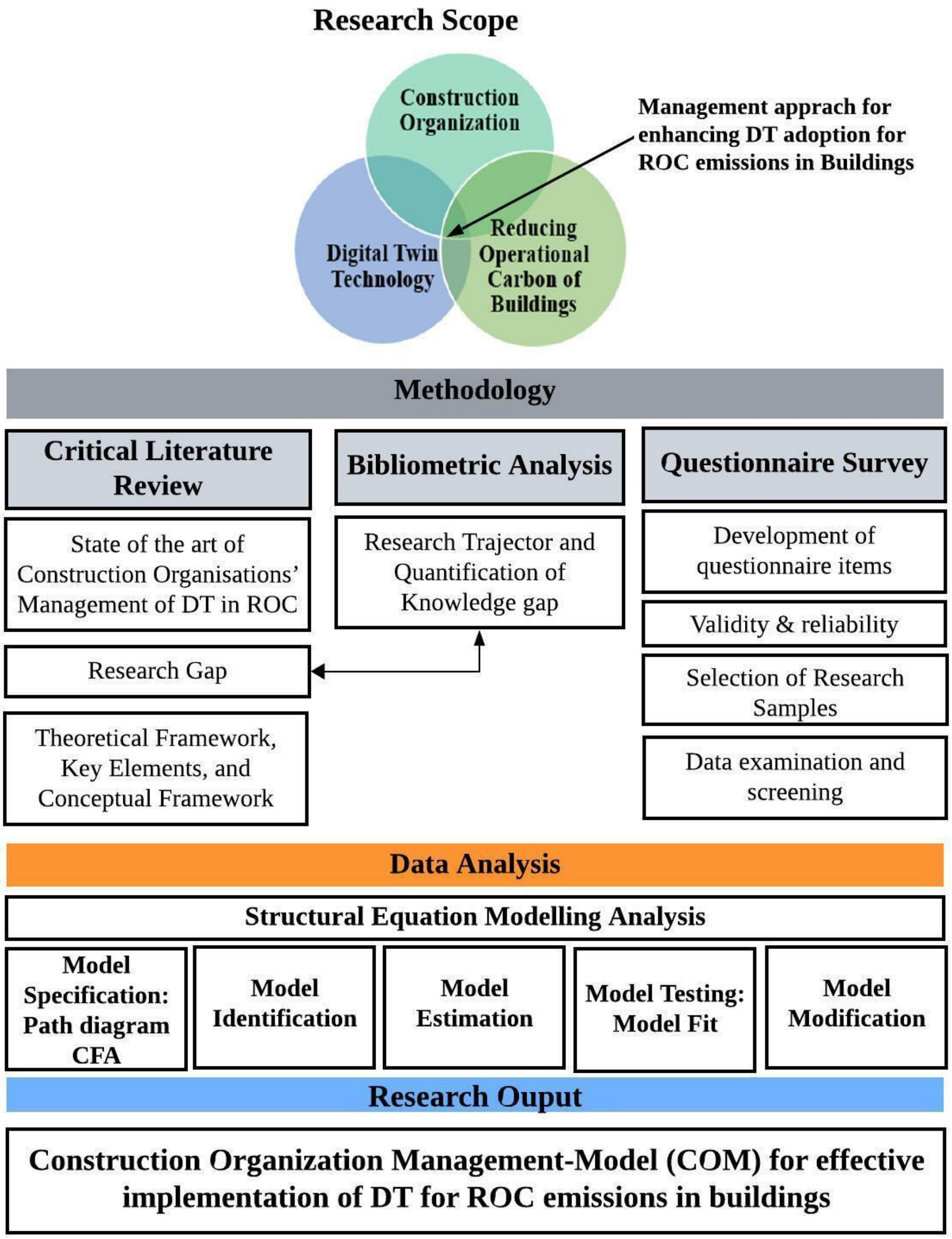

Figure 7: Research Methodological Framework

Quantitative Research Method - Questionnaire Survey

The questionnaire was chosen as the quantitative data collection method due to its efficiency in gathering structured information from a diverse sample of participants (Salameh et al., 2023). The questionnaire used in this research is divided into two sections. Section A was used to gather demographic information about the respondents. Section B identified the key elements of the proposed construction organisation's management model for effective implementation of DT for ROC. A five-point Likert scale was used, ranging from "strongly disagree" (1) to "strongly agree" (5), and the constructs were measured using the variables identified from the literature review (Table 2).

As part of the process of developing the main questionnaire, a preliminary survey was conducted to ensure validity and reliability. Establishing the validity and reliability of a research instrument is crucial for ensuring the study's credibility (Hauashdh et al., 2021). Based on feedback from 5 randomly selected construction experts, the questionnaire was refined, resulting in the reduction of variables from 42 to 36. Variables were eliminated due to their irrelevance and overlap with others. Afterwards, a pilot survey was conducted by distributing the questionnaire to 34 experts from construction organisations and academic institutions. Cronbach's alpha was then used to assess the data. The results are as follows: Technology Adoption (TA: 0.92), Process Reengineering (PR: 0.83), Change Management (CM: 0.78), Complex System Interconnections (CSI: 0.90), Performance Monitoring & Evaluation (PME: 0.80), Government & Stakeholders Involvement (GSI: 0.77), and Construction Organisation Management-Model (COM: 0.87). The reliability analysis shows that all items are reliable, having met the 0.7 thresholds (Nakagawa et al., 2020)

The research population consists of construction experts working in construction companies across the globe who provide a global context for the study. The companies were consulted following the snowball approach, while the respondents were selected based on the Purposive Sampling Technique (PST) due to its convenience in quickly and cost-effectively collecting data from willing participants (Postnikova et al., 2022). While PST may limit generalizability, it allowed the inclusion of professionals from various countries, providing valuable insights into global DT implementation for ROC emissions, ensuring broader real-world applicability (Wuni et al., 2024). Hence, 345 appropriately answered questionnaires were received from the targeted countries.

The demographics of the 345 respondents were examined using descriptive statistics, and the findings unveiled a diverse group with varying locations and backgrounds, as shown in Figure 8.

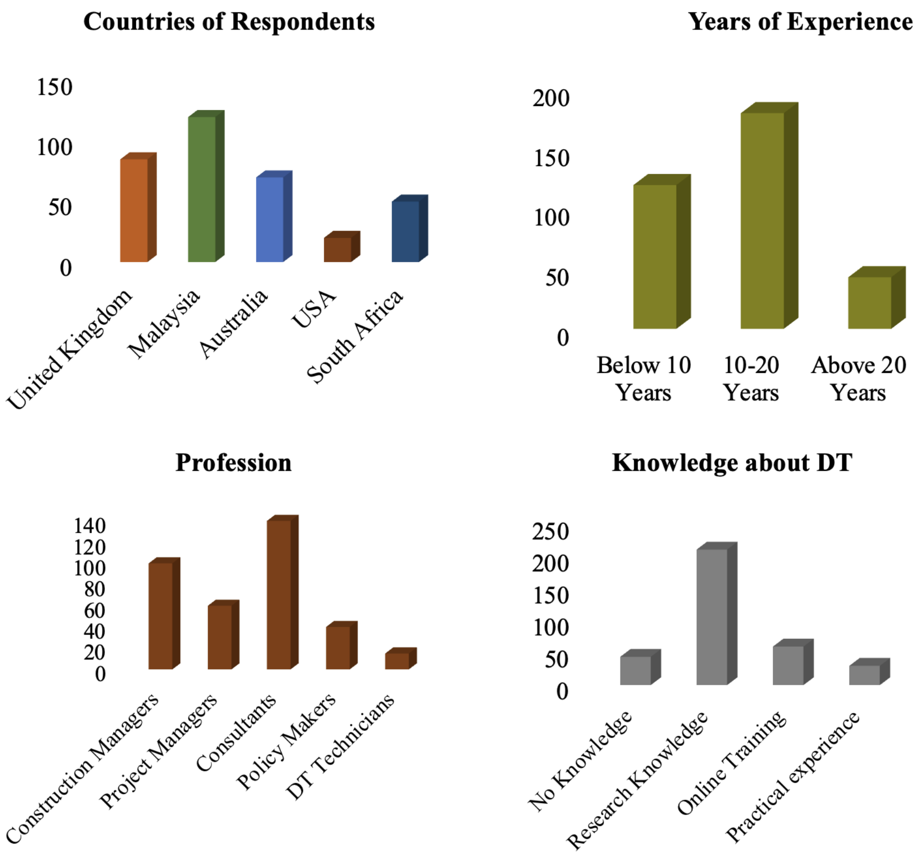

Figure 9: Demographic Analysis of Questionnaire Respondents

Figure 8 clearly illustrates the demographic background of the respondents in the questionnaire. After the demographic analysis, a normality test was conducted on the collected data to determine whether the sample data followed a normal distribution. The normality test is a critical prerequisite for multivariate analysis that assesses the shape of the distribution curve using skewness (negative or positive) and kurtosis (flat or high-peaked) (Ohueri et al., 2023b). The results of the normality test fell within the accepted range of +1 to -1, indicating a normal distribution and ensuring the reliability of subsequent analyses.

Analysis Technique

Structural equation modelling (SEM) was then employed for data analysis. SEM's capacity to model complex relationships, including latent constructs and comprehensively assess overall model fit, makes it preferable to traditional regression analysis (Ohueri et al., 2023). SEM was executed following the five rigorous, systematic and logical steps illustrated in Figure 7. Step 1 is a model specification, which defines the relationships, paths, and hypotheses while validating the indicators via Confirmatory Factor Analysis (CFA) in Analysis of Moment Structure (AMOS) software. Step 2, model identification, ensures the model is estimated to yield reliable results. Model estimation, which is step 3, minimises the differences between theoretical and observed covariance, while step 4, model testing, assesses goodness of fit, parameters, and sample alignment based on predetermined criteria GFI, AGFI, NFI > 0.9, CFI > 0.90, p < 0.05, RMSEA 0.05-0.08, and CMIN/DF < 3. Step 5, model modification, adjusts the fit using trimming or new parameters, such as removing non-critical items with loadings < 0.6.

Afterwards, convergent validity was used to check whether items of a variable contribute to variance, needing an average variance extracted (AVE) of 0.05 or higher. AVE is calculated using this formula:

Equation 1: $AVE = \frac{\sum Standard\ Loading^2}{Number\ Of\ Indicators}$

While divergent validity is used to check unrelated variables. Discriminant validity is confirmed if the square root of AVE exceeds the correlation between latent variables. The validated measurement model was then used to test the research hypotheses. This resulted in the development of SEM.

DATA ANALYSIS AND RESULTS

Measurement Model Evaluation

The measurement model, which consists of seven latent variables such as TA, PR, CM, CSI, PME, GSI, and COM, was specified to assess model fit. The initial result of the analysis showed poor model fit with (p<0.00), CFI (0.86) below the 0.0 accepted threshold, RMSEA (0.08) acceptable, and CMIN/DF was 4.0 above the 3.0 acceptable index. Thus, the model was modified by eliminating variables with factor loading below 0.6, in line with Hair *et al.* (2014) affirmation. Precisely, 6 variables, such as TA4, PR5, CM1, CM5, CSI5, and PME5, were removed from the model due to low factor loading. Hence, the model, which included 29 observed variables, achieved goodness of fit with the following indices: CMIN/DF: 2.76, RMSEA: 0.06, CFI: 0.91, p-value: 0.03, indicating a well-fitted and acceptable model (*Hair et al.,* 2014). After achieving a satisfactory fit, the model underwent validation using Equation 1 as per Ohueri et al. (2023). The Average Variance Extracted (AVE) for all variables exceeded the 0.5 threshold, demonstrating convergent validity. Additionally, the square root of AVE surpassed correlations, affirming discriminant validity. The validated measurement model was then employed to examine the research hypotheses, leading to the development of the structural equation model.

Structural Equation Model (SEM)

The indices of the SEM model indicated a good fit and were consistent with the established measurement model: CMIN/DF: 2.76, RMSEA: 0.06, CFI: 0.91, p-value: 0.03. These fit statistics suggest the model is well-fitted and acceptable (Hair et al., 2014). The structural model exhibited a satisfactory fit without requiring further adjustments, confirming that the SEM model is suitable for hypothesis testing. The SEM is illustrated in Figure 9.

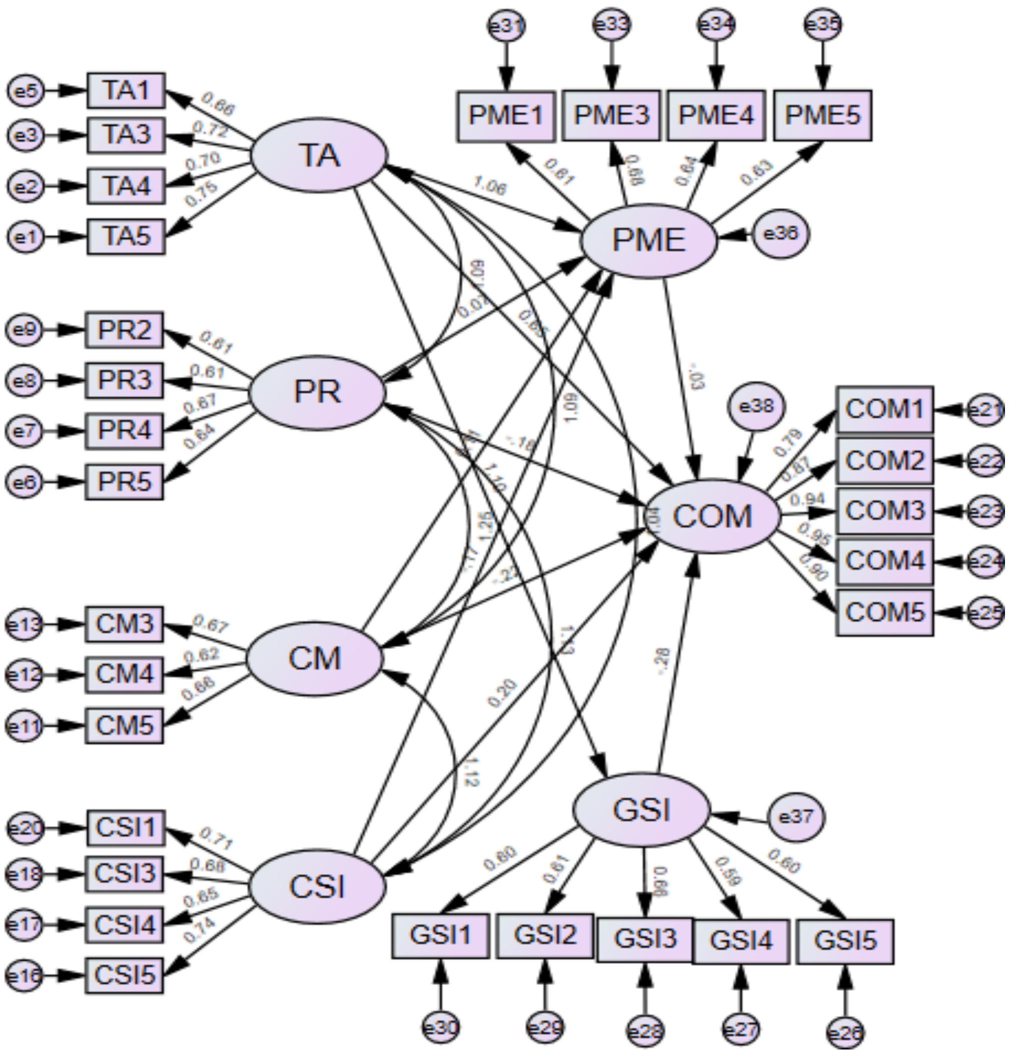

Figure 9: SEM/Construction Organisation Management-Model (COM)

Based on the accepted SEM in Figure 9, the hypotheses of this study were assessed, as depicted in Table 3.

Table 3: Research Hypotheses Testing

Hypotheses	Estimate	S.E.	C.R.	P	Supported?
H1: There is a significant direct relationship between technology adoption strategies and construction organization management of DT for ROC.	.445	.056	.514	.012	Yes
H2: There is a significant direct relationship between process reengineering concept and construction organization management of DT for ROC.	.137	.066	.588	***	Yes
H3: There is a significant direct relationship between change management and construction organization management of DT for ROC.	.678	.077	3.668	.048	Yes
H4: There is a significant direct relationship between complex system interconnections and construction organization management of DT for ROC.	.155	.077	2.45	.045	Yes
H5: Performance monitoring & evaluation mediates the relationship between technology adoption, process reengineering, change management, complex system interconnections, and construction organization management of DT for ROC.	.188	.035	4.667	.032	Yes
H6: Government & stakeholders involvement mediates the relationship between technology adoption and construction organization management of DT for ROC.	.157	.065	2.325	.044	Yes
H7: Performance monitoring & evaluation have a positive significant effect of on construction organization management of DT for ROC.	.657	.088	2.325	.020	Yes

H8: Government & stakeholders' involvement have a positive significant effect of on construction organization management of DT for ROC.	-.452	.025	2.725	.044	No

The result shows that 7 out of the 8 hypotheses of this study are supported. The discussion section elaborates on the hypothesis.

DISCUSSION OF FINDINGS

H1 is supported with a p-value of 0.012, which is within the threshold of 0.05 as shown in Table 3, underscoring the importance of adapting the concept of technology adoption theory as an integral part of the construction organisation's management strategies for driving DT for ROC. As viewed by Sánchez-Prieto et al. (2017), the initial step in implementing technology adoption theory in an organisation is to assess perceived usefulness and ease of use. Thus, the management team of the construction organisation is obliged to use surveys and in-depth interviews to evaluate DT's perceived usefulness and ease of use among employees. Attainment of a positive response rate indicates employees' readiness for DT adoption, serving as a crucial indicator for management to proceed with implementation efforts (Cai et al., 2023). This initial step is pivotal in raising awareness and laying the groundwork for successful DT adoption for carbon reduction. However, in literature and practice, this approach is commonly ignored. Furthermore, evaluating DT compatibility with existing processes and systems is essential (Na et al., 2022). Streamlining the integration process can significantly reduce implementation time and cost, ensuring the organisation realises the full potential of DT for ROC. Additionally, while the importance of demonstrating the tangible benefits of DT adoption is acknowledged, there is a lack of comprehensive guidance on how construction organisations can effectively display these benefits. Hence, Ohueri et al. (2023b) suggest the use of pilot projects as a means to demonstrate DT's effectiveness in reducing emissions. A clear and tangible benefit secures support and commitment.

H2 is supported, aligning with the popular saying, "Do not automate, obliterate." Organisations like Ford have proven that radical redesigning of existing processes yields dramatic performance improvement. According to Sborshchikov et al. (2023), reengineering existing processes requires the construction organisation to thoroughly analyse the management strategies. The carbon reduction strategies ought to be critically evaluated and revitalised with approaches that are more efficient. Afterwards, a digital technology integration assessment is conducted (Alnaser et al., 2024), ensuring seamless integration of DT with established carbon reduction strategies, thereby optimising DT's effectiveness. The need for upskilling to meet the complex DT technology cannot be overemphasised (Ohueri et al., 2023a). Although these practices appear to be common practice, the existing evaluation processes often lack criticality due to the absence of a defined approach. Therefore, targeted carbon reduction criteria should be developed drawing from existing sustainability-rating tools, ISO, etc. (CIDB, 2022). Besides, the level of maturity of DT to be applied should be clearly communicated and must align with the technical expertise and infrastructure (Alnaser et al., 2024). Furthermore, the extent of retrofitting ought to be clearly highlighted. Additionally, a robust data management framework is necessary to ensure seamless data exchange from diverse applications, facilitating informed decision-making (Ohueri, 2022). According to Green et al. (2023), effective process redesign can enhance organisations' efficiency by over 15%.

H3 is supported. This aligns with Prosci's (2024) assertion that addressing the construction organisations' resistance to change will drive the implementation of new technologies. Therefore, it is crucial for construction organisation management to develop a comprehensive change management plan to overcome the persistent resistance (Leung et al., 2021). Integrating change management concepts to enhance the use of DT for ROC emissions fills a critical gap in the literature and industry practices. This plan should provide a roadmap for effectively transitioning from traditional processes to newly defined ones, outlining achievable targets, incentives for success, and the next phases (Halou et al., 2019). According to Dagher and Fayad (2024), it is imperative to foster a work environment where reducing carbon emissions is integrated into the organisation's values and behaviours, aligning with established sustainable development goals and digitalisation endeavours, ensuring old and redundant policies are eliminated. By prioritising these aspects of change management, construction organisations can effectively drive the adoption and successful implementation of DT for ROC emissions in retrofitting practices.

H4 is supported. The integration of DT for ROC is complex, involving diverse applications, heterogeneous carbon criteria, and human engagement. Therefore, the construction organisation management is obliged to cohesively address these complexities (Gong et al., 2023), adapting the concept of the theory of complex systems to establish well-laid-out strategies. Firstly, the management must define the system boundaries (Geng et al., 2021). Specifically, the construction organisation must clearly delineate the boundaries and scope of the system where DT will be integrated, ensuring that all relevant components and stakeholders are identified and accounted for. This includes determining the number of DT technologies that will be deployed, the quantity of IoT sensors to be installed, and specifying the utilisation of emerging technologies such as edge computing, machine learning, blockchain, etc. Byrne and Callaghan, (2022) stressed the need to develop interoperability protocols, such as establishing standardised protocols and interfaces, to enable seamless communication and data exchange between different systems and components within the construction organisation's ecosystem. Gong et al. (2023) emphasised identifying data exchange mechanisms to ensure interoperability. Additionally, Mohanty et al. (2024); Geng et al. (2021) highlighted the need for complex system integration strategies to address issues like data compatibility, scalability, cybersecurity, and privacy.

H5 is supported, emphasising the critical importance of performance monitoring and evaluation (PME) across all elements, particularly in implementing DT for ROC within construction organisations' management. PME rigorously evaluates the effectiveness of technology adoption strategies (Torgautov et al., 2022) by incorporating key performance indicators (KPIs) to assess the influence of awareness on DT, teams' acceptance level for DT, and performance of retrofitted buildings in terms of carbon footprint reduction. The outcome of these assessments enables the management team to provide invaluable feedback to optimise DT deployment for targeted carbon reduction initiatives (Ohueri et al., 2023b). Moreover, PME plays a pivotal role in mediating process reengineering by evaluating the effectiveness of re-engineered processes in achieving the project goal (Geng et al., 2021). This process guides adjustments and refinements as needed, contributing to optimising DT utilisation for targeted carbon reduction. With respect to change management, PME facilitates the evaluation of change initiatives related to DT adoption, enabling the management of construction organisations to identify persistent challenges and adapt strategies for the successful implementation of DT and actualisation of carbon criteria. Also, the PME mediates complex systems by continuously assessing adequacy in the interconnected digital systems (Sborshchikov et al., 2023; Alnaser et al., 2024). Thus. The management of construction organisations should employ data quality assurance for DT-related carbon data and data analysis techniques to guide optimisation and enhance effectiveness in predicting carbon impacts.

H6 is supported and corresponds with CIDB's (2022) report that engagement with regulatory bodies ensures construction organisation compliance with industry standards and regulations, facilitating compatibility with existing processes and systems. Collaboration with government agencies provides best practices and essential incentives required for adequate use of DT for ROC (Ohueri et al., 2023b). Furthermore, engagement with building occupants for feedback ensures user-centric DT solutions. Collinge (2012), Beck and Storopoli (2021), and Wojewnik-Filipkowska et al. (2021) have stressed the crucial roles of government and other stakeholders in driving sustainable technological advancements in construction, emphasising the need for comprehensive government strategies to promote the adoption and management of DT for ROC.

CONCLUSION

This study utilised critical review, knowledge mapping, and quantitative research methods to develop the SEM-based construction organisation management model for the effective implementation of DT to substantially reduce carbon emissions in existing buildings. The novel model draws from various management theories, which were adapted and combined to address the multifaceted issues of implementing DT for ROC, focusing on the management aspect of implementing emerging technologies and achieving carbon reduction criteria. Precisely, the model demonstrates how key elements like technology adoption, process reengineering, change management, and complex system interconnections can be integrated to enable construction organisations to navigate the complexities inherent in utilising human expertise, overarching carbon criteria, and diverse DT applications. In addition, it shows the mediating roles of performance monitoring and evaluation and stakeholders' involvement, ensuring that the aforementioned elements are effectively integrated into the construction organisations' management strategies to achieve the overall goal. This approach is missing in existing literature, and the study fills a significant gap in the literature on DT in retrofitting practices.

This study provides the construction organisation with the unanswered solution of how diverse technologies and vast data can be effectively managed to address practical challenges, which will ensure that the technologies are effectively utilised. Moreover, this study advances efforts in using digitalisation to mitigate carbon emissions, ultimately contributing to global efforts to combat climate change. Future studies should explore extending the COM to other emerging technologies, determining its practical impact on overall sustainability in building and construction.

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