

A Framework for Integrating Digital Ergonomics into Sustainable Construction Site Management

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ABSTRACT

This study is premised on the argument that achieving sustainability in construction site management requires integrating Digital Ergonomics. Accordingly, the objectives of the study are twofold: to examine the benefits of Digital Ergonomics for sustainable construction site management and to develop a framework for its systematic integration into construction site operations. The theoretical foundation of the study is anchored in Socio-Technical Systems theory, which emphasizes the joint optimization of human and technological systems. A qualitative research methodology was adopted through a Systematic Literature Review (SLR) guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. A total of 109 research publications were identified and screened, forming the basis of the analysis. The findings reveal five key benefits of Digital Ergonomics for sustainable construction site management: potential for scenario analysis, GIS-enabled spatial analysis, multimodal interaction, waste reduction and management, and digital lean construction. Furthermore, the study proposes a six-stage integrative framework for embedding Digital Ergonomics into sustainable construction site management, comprising modular construction, sustainability indicators and design for construction sites, a Big Data analytic model, design of human action behavior recognition technology, application of Digital Twin technology, and a biophilic construction site model. The study concludes that Digital Ergonomics serves as a strategic bridge between human-centered design and sustainable, data-driven construction operations. It recommends institutionalizing the twin transitions of digitalization and sustainability within construction site policies and regulatory frameworks, as well as practical experimentation with Digital Ergonomics models across diverse construction contexts.

Keywords: Digital ergonomics, Construction site management, Sustainability, Twin transition, Biophilic construction site model

INTRODUCTION

The sustainability of construction management has been widely discussed in literature; however, limited attention has been given to the enabling role of Fourth Industrial Revolution (4IR) digital technologies and the concept of ergonomics in advancing sustainable construction site management. Much of the existing discourse continues to emphasize traditional approaches to

construction site management, which are often characterized by inefficiencies, resource wastage, fragmented coordination, and operational challenges. Ozumba and Shakantu (2018) highlight the persistent difficulty of integrating digital technologies into construction site management to enhance project success and optimize delivery outcomes. Their study identifies several barriers to technological integration, including technological limitations, insufficient knowledge, managerial constraints, poor network infrastructure, limited information flow, psychological resistance to technology adoption, cost concerns, and low user acceptance. These challenges reflect broader systemic issues within construction environments that hinder digital transformation.

Construction sites also face multifaceted operational problems. Dube, Aigbavboa, and Thwala (2015) categorize these into management and administrative challenges, such as poor information management, inaccurate planning assumptions, and outdated performance measures, and technical challenges, including inadequate plant maintenance, inefficient recording systems, and poor management of utility services. In addition, communication breakdowns among construction professionals further exacerbate inefficiencies on-site. Also, from a supply chain perspective, Thunberg, Rudberg, and Gustavsson (2017) identify additional complexities affecting site performance, including lack of knowledge sharing, limited trust among stakeholders, the absence of workflow planning, unpredictable delivery reliability, changing site layouts, fragmented coordination, and insufficient integration during the design phase. These issues collectively undermine productivity and sustainability objectives.

Consequently, recent research such as Turner et al., (2021) suggests that digitalization offers new opportunities for improving construction safety and productivity through technologies such as robotics, Building Information Modelling (BIM), smart wearables, and Digital Twins, much of this focus remains centered on improving building methods, materials, and machinery. For instance, robotics can enhance site surveying, BIM facilitates real-time access to project information, smart wearables monitor worker movement and environmental conditions, and Digital Twins enable predictive intelligence and real-time simulation of construction activities. Similarly, Mäki and Kerosuo (2015) argue that BIM enhances managerial tasks such as planning, procurement, scheduling, and information retrieval.

However, a critical question remains: to what extent can these digital technologies fully realize their transformative potential in construction site environments from an Ergonomics perspective? While existing applications of digital technologies have largely focused on enhancing productivity and improving worker safety, they remain relatively silent on the intersection between construction site layout design, worker efficiency from an ergonomic perspective, and broader sustainability outcomes. The integration of digital solutions has predominantly emphasized operational performance, with limited consideration of how site configuration, spatial planning, and human–technology interaction influence workers' physical well-being, task efficiency, and long-term site sustainability. In particular, insufficient attention has been given to how digital technologies can be strategically applied to

optimize construction site ergonomics, thereby contributing to sustainable material management, improved energy utilization, waste minimization, and reduced environmental degradation. This is because construction site layout directly affects material-handling distances, equipment positioning, worker movement patterns, and energy consumption, all of which have significant implications for both environmental and social sustainability. Yet, the ergonomic dimension of digital site planning remains underexplored within sustainability discourse. This study addresses this notable research gap by examining how digitalization can be systematically integrated with ergonomic principles to enhance sustainable construction site management. This is because, it is insufficient for digital transformation in construction to focus solely on productivity gains without simultaneously advancing sustainability objectives and improving worker-centered design.

According to the International Ergonomics Association (IEA), ergonomics is defined as “the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance” (IEA, 2000). This definition highlights both the theoretical and applied dimensions of ergonomics, emphasizing its dual objective of enhancing human welfare while improving system efficiency. Amjad et al. (2023) further posits that ergonomics improves task design to suit human capabilities, thereby enhancing operational efficiency and boosting productivity. Similarly, Eilouti (2022) describes ergonomics as the interaction between humans and their environment, reinforcing its systemic and contextual nature.

The practical relevance of ergonomics is evident in established ergonomic assessment tools such as Rapid Upper Limb Assessment (RULA), which focuses on evaluating strain in the upper extremities including wrists, arms, and neck, and Rapid Entire Body Assessment (REBA), which provides a holistic evaluation covering the entire body, as discussed by Zubair et al., (2025). Golabchi et al., (2018) further argue that ergonomics enhances human safety, well-being, and productivity among construction workers when the workplace environment is properly designed and conducive to human functioning. Fundamentally, ergonomics seeks to establish a balance between the area of operation (work environment), the object of operation (tools and materials), and the subject of operation (the worker). In construction site contexts, ergonomics can therefore be understood as focusing on the design and configuration of site layouts and operational systems that directly influence worker productivity, safety, and efficiency.

Morton, Luliak, and Renger (2025) identify three major dimensions of ergonomics: physical ergonomics, which focuses on workplace design, posture, and physical safety; cognitive ergonomics, which addresses mental workload reduction, decision-making support, and interface usability; and organizational ergonomics, which emphasizes the alignment of teamwork structures, management systems, and digital workflows with employee well-being. When ergonomics is combined with digitalization, forming what is referred to as Digital Ergonomics, its scope expands further. Hovanec et al.

(2024) note that Digital Ergonomics supports the digitalization of safety management, quality of work, and maintenance processes. Thus, applying Digital Ergonomics on construction sites involves optimizing the relationship between construction site layout and the comfort, safety, productivity, and ease of operation of construction workers through the deployment of advanced technologies such as BIM, sensors, wearables, simulation tools, and data analytics.

Moreover, as earlier indicated, the central focus of this study is to examine how Digital Ergonomics contributes to sustainable construction site management. Zajemska et al., (2025) assert that sustainable construction emphasizes the efficient use of resources, the integration of green design principles, and the harmonization of residential and commercial developments with natural ecosystems, particularly through careful material selection and environmentally responsible practices. Díaz Caselles and Guevara (2024) further analyze sustainability Key Performance Indicators (KPIs) within onsite construction across environmental, social, and economic dimensions, highlighting performance areas such as profit optimization, cost control, labor conditions, customer satisfaction, community impact, resource utilization, and contaminant management.

Accordingly, the sustainability of construction sites extends beyond environmental considerations alone. It encompasses how construction processes, outputs, methods, working conditions, and site environments collectively contribute to optimal resource allocation and utilization, improved working conditions, cost effectiveness, enhanced productivity, and reduced environmental degradation. Sustainable construction site management, therefore, requires a holistic integration of operational efficiency, worker well-being, and environmental stewardship. In light of these considerations, the cardinal objective of this study is the development of a framework for integrating Digital Ergonomics into sustainable construction site management. To achieve this overarching objective, the study pursues two specific objectives:

- a. To examine the benefits of Digital Ergonomics for sustainable construction site management.
- b. To develop a framework for integrating Digital Ergonomics into sustainable construction site management.

This study is significant across four major domains. First, it contributes to scholarly literature by advancing research that systematically optimizes the relationship between Digital Ergonomics and sustainable construction site management, thereby addressing a notable gap in existing studies. Second, it contributes to the productivity and health of construction workers, as insights from the study can inform the development of predictive and prescriptive safety systems, enhance cognitive balance, and support mental alertness on construction sites. Third, it benefits construction firms by enabling improved project delivery through optimized resource use, cost effectiveness, enhanced operational efficiency, and profitability maximization. Fourth, it provides valuable input for policy and regulatory frameworks by informing

contemporary guidelines for the planning and management of construction sites, moving beyond traditional mechanisms toward digitally enabled and sustainability-oriented site management systems.

Theoretical Perspectives

This study is anchored in the Socio-Technical Systems (STS) Theory, which provides a suitable theoretical foundation for examining the interaction between human dynamics and technological systems in the integration of Digital Ergonomics and sustainable construction site management. The theory emphasizes that organizational performance is optimized when social systems (people, structures, behaviors, and culture) and technical systems (tools, technologies, and processes) are jointly designed and harmonized rather than treated independently. Yu, Xu, and Ashton (2023) explain that socio-technical systems theory focuses on learning processes and behavioral interactions between humans and technology, highlighting the reciprocal relationship that enables productivity without undermining either dimension. The theory promotes a “win-win” outcome in which technology enhances working conditions while human adaptability and engagement enhance technological effectiveness. It advocates joint optimization, ensuring that both social aspirations (well-being, satisfaction, safety) and technical aspirations (efficiency, performance, innovation) are simultaneously achieved.

Similarly, Zhang et al. (2023) argue that socio-technical systems theory examines how technological systems influence societal progress and organizational performance. From a firm-level perspective, the interaction between technological infrastructure and social structures shapes behavior, productivity, innovation capacity, and long-term sustainability. This perspective reinforces the idea that technological adoption alone does not guarantee improved outcomes unless it is aligned with human capabilities and organizational context. Therefore, in relation to this study, the social dimension of the theory is represented by ergonomics, which addresses human needs, physical and psychological well-being, cognitive workload, and working conditions on construction sites. Ergonomics ensures that construction site layout, task design, and operational processes are structured to support worker comfort, safety, efficiency, and mental alertness. The technological dimension is represented by digitalization, particularly the application of Fourth Industrial Revolution (4IR) technologies such as Building Information Modelling (BIM), Digital Twins, smart wearables, sensors, robotics, and data analytics to enhance ergonomic performance on construction sites.

Consequently, the integration of these two dimensions of social (ergonomics) and technical (digitalization) is expected to produce a mutually reinforcing outcome: the sustainability of construction site management. When digital technologies are applied to enhance ergonomic conditions and ergonomic principles guide technological deployment, construction sites can achieve improved worker well-being, higher productivity, optimized resource utilization, and enhanced sustainability performance. Thus, within the socio-technical framework, Digital Ergonomics serves as a mechanism for joint

optimization, resulting in sustainable construction sites that benefit human actors while simultaneously maximizing the efficiency and value of digital technologies.

Research Methodology

The objectives of this study were achieved through a qualitative research methodology, which enables deeper, more comprehensive insights from non-numeric, contextually rich data. Qualitative research answers research questions through systematically defined procedures that generate new understanding about a subject matter (Oranga & Matere, 2023). Unlike quantitative approaches that focus on “how much” or “how many,” qualitative research addresses “how” and “why” questions (Moser & Korstjens, 2018), making it particularly suitable for this study, which seeks to explore how Digital Ergonomics can be integrated into sustainable construction site management and why such integration is necessary. Accordingly, this study adopted a Systematic Literature Review (SLR) as its primary methodological approach. A systematic literature review enables the structured identification, evaluation, and synthesis of existing knowledge relevant to a defined research objective (Adepoju, Nwulu & David, 2022). The SLR approach ensures transparency, replicability, and rigor in the review process, thereby reducing bias in literature selection and analysis.

To ensure a systematic and transparent review process in uncovering the benefits of Digital Ergonomics for sustainable construction site management and in developing a framework for integration, this study followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (David et al., 2023), which provides a structured flow process for identification, screening, eligibility, and inclusion of relevant studies. According to Tedja et al. (2024), the PRISMA process involves sequential steps of database identification, screening based on predefined criteria, eligibility assessment, and final inclusion of relevant literature.

Determination of the Source of Information

The study utilized literature from the Scopus database due to its extensive coverage of peer-reviewed journals, conference proceedings, and book chapters across multidisciplinary domains (David et al., 2022). Scopus was selected for its broad indexing scope, reliability, and reputation for publishing high-quality scholarly publications compared to other scholarly databases.

Study Selection

The literature retrieved from the Scopus database was based on the core keywords reflected in the title of this study, namely: “Digital,” “Ergonomics,” “Construction Site,” and “Sustainability.” An initial search combining all keywords simultaneously returned no results, further reinforcing the research gap this study seeks to address: the absence of integrative research that combines these four research areas. To address this limitation, the search strategy was structured into three streams across the Title, Abstract, and

Keywords fields, yielding a total of 109 documents. The search queries were as follows:

- a. (TITLE-ABS-KEY (“Ergonomics”) AND TITLE-ABS-KEY (“Digital”) AND TITLE-ABS-KEY (“Construction Site”)) – 55 papers
- b. (TITLE-ABS-KEY (“Construction Site”) AND TITLE-ABS-KEY (“Sustainability”) AND TITLE-ABS-KEY (“Ergonomics”)) – 5 papers
- c. (TITLE-ABS-KEY (“Construction Site”) AND TITLE-ABS-KEY (“Digital”) AND TITLE-ABS-KEY (“Sustainability”)) – 49 papers

These three streams allowed the study to capture relevant literature at the intersection of the core thematic areas, even where full integration had not yet been explicitly explored in prior research.

Data Collection and Eligibility

The retrieved literature was subjected to defined eligibility and ineligibility criteria to ensure relevance and quality. The eligibility criteria included studies published in English and categorized as journal articles, conference papers, book chapters, or books. The ineligibility criteria excluded errata, documents written in languages other than English, and papers in press to ensure stability and accessibility of the reviewed sources. Therefore, following the screening and eligibility assessment stages, a total of 90 papers were retained for final analysis.

Data Analysis

The final selected studies were analyzed using conventional content analysis, as proposed by Hsieh and Shannon (2005). Under this approach, the selected literature was systematically reviewed to identify recurring themes, which were coded and categorized for the benefit of Digital Ergonomics, sustainability dimensions, and integration pathways. The analysis enabled the synthesis of existing knowledge and facilitated the development of the proposed framework for integrating Digital Ergonomics into sustainable construction site management.

DISCUSSION

Benefits of Digital Ergonomics for Sustainable Construction Site Management

In examining the benefits of Digital Ergonomics for sustainable construction site management, it is essential to first highlight its inherent advantages. Digital Ergonomics extends traditional ergonomic principles by applying advanced digital technologies, thereby enhancing the capacity to anticipate, monitor, and optimize human–technology interactions in dynamic construction environments. One of the primary benefits of Digital Ergonomics is its predictive and prescriptive capability. Digital technologies enable the prediction of potential injury risks and the identification of preventive

mechanisms before incidents occur. Zhang, Nieuwenhuys, and Zhang (2025) note that digital systems can predict posture-related risks across the entire body and identify unsafe ergonomic patterns in advance. Similarly, Sen et al., (2024) affirm that machine learning models can be applied to workplace ergonomics to forecast risk exposure and minimize ergonomic hazards through data-driven insights. These predictive capabilities shift construction site management from reactive safety practices to proactive and preventive strategies.

In addition, Digital Ergonomics facilitates real-time recognition of human behavior. Peng et al. (2024) highlight that digital technologies enable continuous monitoring of construction workers' movements and behaviors, thereby supporting the design of context-specific risk-mitigation and safety mechanisms. According to the authors, such systems enhance understanding of the interaction between physiological and psychological factors, enabling the identification, prediction, and prevention of unsafe behaviors while also prescribing appropriate corrective interventions. This integration of behavioral analytics and ergonomic monitoring strengthens decision-making processes and enhances worker-centered site management.

Therefore, applying the concept of Digital Ergonomics within sustainable construction site management introduces a transformative approach to site operations. It establishes a causal chain of benefits that extends beyond individual worker safety to influence overall site sustainability performance. Through predictive analytics, behavioral monitoring, and digital optimization of ergonomic conditions, construction sites can improve resource allocation, reduce inefficiencies, enhance workflow coordination, and minimize material and energy waste. Therefore, based on findings synthesized from the systematic literature review, drawing from studies including Peng et al. (2024), Weerapperuma et al. (2024), Piras, Muzi, and Tiburcio (2024), David et al. (2022), Brunner, Knott, and Bengler (2022), Liu, Yi, and Wang (2020), Ning et al. (2010), and Fan (2009), five principal benefits of Digital Ergonomics for sustainable construction site management were identified. These benefits collectively demonstrate that integrating digital technologies with ergonomic principles improves sustainability outcomes across construction site operations.

The identified benefits of Digital Ergonomics for sustainable construction site management are as follows:

a. Potential for Scenario Analysis: This benefit involves understanding, simulating, and evaluating different operational dynamics and scenarios within a construction site environment, and how these scenarios may affect worker productivity, health, safety, cognitive balance, overall well-being, and working conditions. Working conditions in this context include factors such as working hours, thermal comfort, air quality, and acoustic comfort. Through Digital Ergonomics, advanced digital technologies, particularly Artificial Intelligence (AI), Digital Twin systems, and the Internet of Things (IoT) can be deployed to conduct predictive scenario analyses. Such simulations enable construction managers to test various site layout configurations, equipment placements, workflow arrangements, and environmental conditions before

implementation. As a result, equipment, resource allocations, energy usage patterns, and site configurations that may be detrimental to worker efficiency or environmental performance can be identified and adjusted accordingly. This proactive approach enhances sustainability outcomes by ensuring that construction sites are optimized for both human performance and resource efficiency. This is as the functionality and sustainability of a construction site are intrinsically linked to the well-being and effectiveness of the workers operating within it.

b. GIS-Enabled Spatial Analysis: The location, topography, and physical characteristics of construction sites significantly influence layout design, equipment positioning, material storage areas, and site accessibility. Poor spatial planning often results in inefficiencies, increased physical strain, unnecessary material movement, and unsustainable construction practices. Through Digital Ergonomics, Geographic Information Systems (GIS) can be integrated into construction site planning to enable spatially informed and ergonomically sensitive layout design. GIS-enabled spatial analysis enables the strategic placement of materials, equipment, and access routes to minimize travel distances, reduce physical strain, enhance workflow efficiency, and improve navigability for workers. By embedding ergonomic considerations into spatial planning, both environmental and social sustainability dimensions are strengthened. Environmentally, optimized layouts reduce fuel consumption, energy usage, and material waste. Socially, improved accessibility and safer navigation enhance worker well-being and productivity.

c. Multimodal Interaction: Construction sites involve complex interactions between human senses, in areas of visual, auditory, tactile, and cognitive inputs, and the surrounding physical and digital environment. These interactions, if poorly managed, may contribute to unsustainable practices such as resource waste, improper debris disposal, unsafe shortcuts, and strained collaboration among construction professionals, often undertaken in the interest of convenience or time pressure on construction sites. Therefore, through Digital Ergonomics, multimodal interaction systems can be deployed to monitor and interpret human responses to environmental stimuli in real time. By integrating sensor technologies, wearable devices, and behavioral analytics, construction managers can predict patterns of unsustainable behavior and intervene proactively. This capability enhances decision-making, improves compliance with sustainability protocols, and fosters more harmonious coordination among workers. As a result, both operational efficiency and environmental responsibility are strengthened.

d. Waste Reduction and Management: Waste generation remains a significant challenge in construction site management. Digital Ergonomics contributes to waste reduction by modeling worker behaviors, task execution patterns, and workflow inefficiencies that may lead to material losses or hazardous waste generation. By analyzing these patterns, digital systems can identify appropriate incentive structures and operational adjustments that encourage waste minimization. Such measures include minimizing design and documentation errors that lead to rework, implementing Just-in-Time

(JIT) delivery strategies, promoting waste recycling initiatives, optimizing material handling and unloading processes, selecting sustainable construction materials, preventing the prolonged use of faulty equipment, and designing efficient routing systems that reduce the distance between storage facilities and points of use. These strategies contribute to environmental sustainability by reducing material waste, lowering energy consumption, and improving site cleanliness and safety.

e. Digital Lean Construction: The operational processes and workflow mechanisms on construction sites significantly influence overall project delivery, resource utilization, and long-term asset performance. By integrating Digital Ergonomics, the pursuit of efficient, worker-centered working conditions naturally aligns with the principles of lean construction. Digital tools support continuous monitoring, performance optimization, and elimination of non-value-adding activities. Digital Lean Construction enhances project delivery mechanisms by improving maintenance planning, asset management, space utilization, and optimized production methods. This integration fosters streamlined operations, reduced downtime, minimized waste, and improved coordination across project stakeholders. The convergence of lean principles and ergonomic optimization, sometimes referred to as Lean Ergonomics, represents an emerging sub-discipline that strengthens the sustainability of construction site management by aligning human efficiency with operational excellence.

Framework for Integrating Digital Ergonomics into Sustainable Construction Site Management

Building upon the five (5) identified benefits of Digital Ergonomics for sustainable construction site management, this study proposes an integration pathways framework designed to ensure that these benefits are systematically realized and optimized. The framework translates the conceptual advantages of Digital Ergonomics into actionable strategies that guide implementation on construction sites. Consequently, drawing on the findings of the Systematic Literature Review (SLR), the framework comprises a set of interrelated strategies that collectively support the integration of Digital Ergonomics into sustainable construction site management. These strategies are designed to be implemented sequentially to ensure structured adoption, progressive alignment, and full optimization of digital ergonomic integration.

Importantly, this framework's effectiveness depends on a prior understanding of the sustainability-related risks inherent in construction site operations. The identification and assessment of these risks determine the appropriate level of digital integration, the nature of ergonomic interventions, and the extent of operationalization required. In other words, risk assessment serves as the foundational diagnostic layer that informs the integration process. According to Coskun, Dikmen, and Birgonul (2023), key construction site risk factors include adverse physical site conditions, unforeseen weather events, design complexity, low constructability, unavailability or defects in construction materials, operational site constraints, ineffective waste management systems, and the absence of structured audits for monitoring waste practices. These

risks not only affect project performance but also influence worker safety, productivity, and environmental sustainability outcomes.

Furthermore, WTW (2024) identifies pollution as a major risk during construction project execution. Pollution risks manifest in multiple forms, including historical contamination, soil pollution, water pollution, air pollution, odor emissions, and biodiversity loss. These environmental risks directly undermine sustainability objectives and reinforce the need for proactive, digitally enabled ergonomic systems that can monitor, predict, and mitigate such impacts. Therefore, the proposed framework recognizes risk assessment as the entry point for integration. By aligning Digital Ergonomics strategies with identified sustainability risks, construction site management can achieve targeted interventions that simultaneously enhance worker well-being, operational efficiency, and environmental performance. This risk-informed, sequential integration model ensures that Digital Ergonomics is not adopted as an isolated technological upgrade but as a strategic mechanism for advancing sustainable construction site management.

a. Modular Construction: Modular construction focuses on reducing extensive on-site production of construction components, thereby optimizing working conditions for construction workers and minimizing stress and inconvenience in congested construction environments. By shifting significant portions of production to controlled off-site facilities, construction sites become less crowded, more organized, and ergonomically efficient. According to Parracho et al. (2025), integrating digital technologies into modular construction is transformative, enhancing planning effectiveness, precision, accuracy, and overall sustainability performance. Based on various case studies, the authors identify both active and passive building solutions resulting from this integration. Active building solutions include HVAC systems, photovoltaic panels, solar thermal systems, heat pumps, radiant floors, hybrid PV/T systems, phase change materials (PCM), biomass systems, wind energy, and geothermal energy. Passive building solutions include thermal insulation, direct solar gains, natural lighting, shading systems, natural ventilation, airtightness, water harvesting systems, green roofs, PCM, green walls, off-grid systems, and automation systems. These solutions enhance construction site sustainability while simultaneously improving ergonomic conditions for the construction workforce through better environmental and operational conditions.

b. Sustainability Indicators and Design for Construction Sites: The adoption of modular construction should be complemented by a clear understanding of sustainability indicators during the design and planning of construction sites, including modular construction environments. These indicators ensure that sustainability principles are embedded within operational processes, workforce mindset, and the overall construction environment. Díaz Caselles and Guevara (2024) identify sustainability indicators across environmental, social, and economic dimensions. Environmental indicators include material, energy, water, and chemical product utilization, as well as contaminants such as air emissions and pollution. Social indicators encompass labor rights, working conditions, labor well-being, labor satisfaction, customer

satisfaction, community and societal well-being, and community satisfaction. Economic indicators include costs for raw materials, packaging, fixed assets, depreciation, labor, environmental fines, utilities, defective products, research and development, training, advertising and promotion, and profitability through revenue generation, subsidies, or tax relief. These indicators guide how construction sites are shaped, organized, structured, and designed to ensure sustainability while avoiding negative impacts on workforce ergonomics. In this regard, the digitalization of ergonomics influences how sustainability indicators are operationalized and measured within construction site management.

c. Big Data Analytic Model: The Big Data analytic model involves the use of large-scale data analytics to understand historical construction site performance in relation to worker productivity, well-being, cognitive balance, and safety or accident occurrence. Big Data technologies can analyze vast volumes of historical data, including petabytes of structured and unstructured data. When combined with Artificial Intelligence (AI), Big Data analytics can also generate predictive insights and forecast future trends (Peng et al., 2025). This predictive capability informs the appropriate level of Digital Ergonomics integration required to enhance construction site sustainability, based on both historical performance data and projected future scenarios. Consequently, data-driven decision-making strengthens the alignment between ergonomic optimization and sustainable construction outcomes.

d. Design of Human Action Behavior Recognition Technology: The preceding integration pathways should inform the design of Human Action Behavior Recognition Technology. This involves structuring systems that capture and analyze workers' activities, actions, reactions, well-being, behavioral tendencies, propensity for Work-related Musculoskeletal Disorders (WMSDs), safety alignment, and likelihood of accidents in ways that optimize Digital Ergonomics for sustainable construction site management (Peng et al., 2025; Rwamamara & Simonsson, 2018). Tao et al. (2024) emphasize the need for ergonomic risk assessment using both vision-based techniques (such as depth and RGB cameras) and sensor-based techniques (including Inertial Measurement Units (IMUs), wearable insole sensors, and Electromyography (EMG)). These technologies support postural assessment, body movement tracking, sequential plantar pressure capture for identifying awkward working postures, and measurement of internal muscle strain and movement. The findings from these assessments can be integrated into the design of Human Action Behavior Recognition Technology to enhance employee work performance. This ensures that construction sites are not designed or laid out in ways that negatively affect the workforce, thereby prioritizing sustainability dynamics alongside ergonomic efficiency.

e. Application of Digital Twin for Construction Sites: According to David et al. (2022), Digital Twin technology involves replicating a physical entity or system in a virtual environment, enabling real-time simulation of behavior and performance. All preceding insights derived from the integrative pathways should be incorporated into a Digital Twin model of

the construction site. Therefore, within this virtual environment, the effects, impact levels, and performance outcomes of construction site sustainability and Digital Ergonomics can be simulated, tested, and analyzed under real-time scenarios. Furthermore, Peng et al. (2025) suggest that Human–Computer Interaction (HCI) elements, such as interaction design, eye tracking, multimodal interaction, electroencephalogram (EEG), and virtual reality, can be integrated into Digital Twin systems to optimize performance and user engagement.

f. Biophilic Construction Site Model: Obiozo and Smallwood (2014) note that construction workers spend approximately 85% of their working time on construction sites. Consequently, Digital Ergonomics becomes essential, and its sustainability directly influences worker output and overall project performance. Given the integration of digitalization strategies, sustainability metrics, and implementation pathways, the ultimate objective of sustainable construction site management is the development of a Biophilic Construction Site Model. This model involves incorporating nature-based solutions into construction environments, grounded in humanistic values. When combined with digital technologies and data-driven insights, the construction site becomes more humane, contributing to worker comfort, reduced heat stress, enhanced psychological benefits, increased work effectiveness, reduced absenteeism, and improved long-term return on investment (Obiozo & Smallwood, 2014). However, it remains essential to emphasize the role of digitalization in ensuring accuracy, precision, and effective human–computer interaction in the implementation and management of biophilic construction site models.

The six integration pathways are structured progressively to form a coherent and layered framework. The process begins with Modular Construction and Sustainability Indicators, which establish the structural and performance foundation for sustainable site design. This is followed by the Big Data Analytic Model, which provides historical and predictive intelligence to guide informed decision-making. Insights from these stages inform the Design of Human Action Behavior Recognition Technology, ensuring that worker-centered ergonomic data is embedded in operational systems. These elements are then consolidated within a Digital Twin environment, where sustainability and ergonomic performance can be simulated, tested, and optimized in real time. The framework culminates in the Biophilic Construction Site Model, representing the holistic integration of digitalization, ergonomics, and sustainability into a humane, efficient, and environmentally responsive construction site ecosystem.

CONCLUSION

This study has established that Digital Ergonomics significantly contributes to the sustainability of construction sites through its identified benefits and the proposed integrative framework. By synthesizing insights from the literature on digitalization, ergonomics, and sustainability, the study extends existing knowledge on construction site management, worker productivity, and industry practices in site selection, planning, and operational setup. In

conclusion, this research positions Digital Ergonomics as a strategic bridge between human-centered design and sustainable, data-driven construction operations. Through the proposed sequential integration pathway culminating in a biophilic, digitally enabled construction site model, the study provides both theoretical advancement and practical implementation guidance for achieving the twin transition of digitalization and sustainability in construction site management. Accordingly, two key policy recommendations emerge from this study. First, there is a need to institutionalize the twin transition of digitalization and sustainability within construction site policies, regulatory frameworks, and operational guidelines. Second, there is a need for practical experimentation and pilot implementation of Digital Ergonomics models on construction sites through relevant technologies such as Artificial Intelligence (AI) modeling and Digital Twin systems, with careful consideration of contextual, geographical, and project-specific dynamics.

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