International Journal of Modern Achievement in Science, Engineering and Technology (IJSET)
ISSN 3023-459X
DOI: 10.63053/ijset.70

How to Digitize for Sustainable Buildings: Technologies, Applications, Potentials and Challenges

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ARTICLE INFO

Keywords:
Internet of Things, digital technologies, sustainable buildings

ABSTRACT

The link between digital technologies and sustainability in the built environment has drawn increasing research interest in recent years. However, the understanding of the use of digital technologies and their impact on construction processes is fragmented. The aim of this study is to evaluate the diverse application areas of digital technologies in the construction industry, with the goal of gaining insights into the potential benefits, challenges, and opportunities for enhancing efficiency, productivity, and overall performance. This helps us understand how innovative technologies can improve various stages of construction projects. To address this gap, this study conducts a systematic literature review of sustainable construction to analyze and synthesize research findings regarding the application of digital technologies in different stages of the construction life cycle. We performed a deep content analysis of 72 articles. The findings indicate that prominent digital technologies for construction sustainability include Building Information Modeling (BIM), the Internet of Things (IoT), Big Data, and Artificial Intelligence (AI). The insights from this study provide valuable information on the effective use of digital technologies in the construction industry, thereby aiding informed decision-making and improving project management practices. We also recognize that the application of digital technologies for sustainability throughout the construction life cycle can be categorized into four areas: (1) integration and collaboration, (2) optimization, simulation, and decision-making, (3) tracking, monitoring, and control. Based on existing knowledge gaps, future research opportunities are identified, including the development of integrated and collaborative systems, long-term performance and flexibility, and advanced simulation and modeling techniques.

Introduction

The construction industry is not merely about building structures and infrastructure. It plays a vital role in economic and social development, contributing nearly $200 billion to the global GDP and creating over 220 million jobs. This sector encompasses a continuous life cycle that integrates design, construction, operation, maintenance, and end-of-life, where each stage is interconnected and linked to the overall performance and sustainability of the built environment. The initial design lays out a framework for the sustainable and efficient use of resources, which is realized during the construction phase (Wang et al., 2014; Bao et al., 2022). The operation and maintenance phase extends throughout the longest stage of a structure's life cycle, emphasizing energy efficiency and environmental monitoring. Finally, end-of-life is a critical component in the recycling and reuse of materials (Sánchez-Garrido et al., 2022; Beccali et al., 2015).

The construction industry has long been associated with significant environmental impacts, including resource consumption, waste generation, and carbon emissions. It produces 45 to 65 percent of waste sent to landfills and accounts for 35 percent of global CO_2 emissions (Lima et al., 2021; Vinuesa et al., 2020). With the international community's increasing focus on sustainable development, the construction sector faces the necessity for evolution. Sustainable practices meet present needs without compromising the ability of future generations to meet their own. Therefore, "construction sustainability" refers to the implementation of such practices within the construction industry, encompassing three main dimensions: environmental protection, social responsibility, and economic durability (Zavadskas et al., 2018; Shelbourn et al., 2006).

In response to sustainability challenges, digital technologies present a transformative potential. Digital technologies include information and communication technologies that manage information through the binary digital computer language. In construction, they range from independent systems to integrated web-based technologies that aid in the collection, storage, processing, presentation, and communication of data during various logistical stages. By streamlining processes, reducing waste, and enabling better decision-making, digital technologies promise to significantly advance the sustainability agenda in construction.

The technologies aligned with the Fourth Industrial Revolution have transformed the landscape of several industries by integrating automation and digitization into their activities and processes (Aghimien et al., 2022). These digital technologies are often described as smart technologies due to their self-executing, self-monitoring, and self-organizing capabilities for predefined tasks (Hwang et al., 2022). Additionally, these smart technologies have been accompanied by innovation adoption, optimizing work and improving performance. Recently, the use of digital technologies has rapidly increased in fields such as aviation, commerce, education, energy, finance, healthcare, and several others. For the construction industry to undergo similar digital transformations as other sectors, there is a fundamental need to harness the potential of digital technologies at both management and field levels. This includes integrating digital technologies into project planning, execution, monitoring, and data analysis, ultimately leading to improved project outcomes, cost efficiency, and safer working environments. Given the adverse effects of construction activities on the environment, such as waste generation, air pollution, noise pollution, climate change, and several other issues (Bodenko et al., 2022), the need for digital technologies to address these challenges worldwide has intensified. Furthermore, considering the low productivity rates in the construction sector, often resulting from a heavy reliance on traditional manual labor, a lack of appropriate standards, and inadequate project management practices (Ibrahim et al., 2022), the need for the implementation of digital technologies cannot be overstated. However, the construction sector, due to its fragmented nature involving a wide range of stakeholders, is often regarded as a slow adopter of digital technologies, each having its own set of processes, standards, and preferences (Botha, 2023).

Despite the growing recognition of their potential, the academic landscape presents a fragmented understanding of the impact of digital technologies on sustainability in construction. Research studies vary in terms of focus, methodology, and findings, making it challenging to create a cohesive perspective on the role of digital technologies in promoting sustainability for industry stakeholders. This fragmentation is a critical barrier to effectively leverage digital technologies for sustainable construction practices. To fill this knowledge gap, this study conducts a systematic review of the literature on construction sustainability. The aim is to gather, analyze, and synthesize research findings to provide a clear and coherent picture of how digital technologies can be utilized to enhance sustainability in construction. By critically examining the interaction between the application of digital technologies and sustainable practices, our goal is to identify successful strategies and highlight areas that require further exploration.

Research Methodology

This study relies on a structured literature review methodology in the field of construction research, aiming to clarify the intersections of digital technologies and construction sustainability through a systematic literature review designed to ensure an objective and replicable synthesis of existing research. Such a structured approach reduces reliance on simplistic judgments, mitigates biases and systematic errors, and maintains the integrity of scientific research. The systematic literature review involves two stages. The first stage defines the research objectives and conceptual boundaries to ensure a focused review. Specifically, it targets current and emerging trends in digital technologies within construction sustainability. Concurrently, conceptual boundaries are defined to delineate the scope of "digital technologies," "sustainability," and "the construction industry." This dual stage ensures that the literature review remains focused and relevant. The second stage involves a comprehensive search strategy and its implementation. This includes selecting an appropriate database, which, given the nascent and interdisciplinary nature of this field, must be extensive. We utilized the Web of Science (WoS) publication database, which includes indices such as SCI, SCI-Expanded, SSCI, A&HCI, and ESCI. Considering the evolving terminology in digital technologies for sustainability in construction, a thorough search string with varying phrases was formulated and applied to the WoS database. This search temporarily includes articles published up to October 2023 to ensure contemporary relevance. A total of 790 articles are presented for further processing. Subsequently, a manual filtering process is applied, where articles are carefully screened against predefined criteria. For instance, non-English articles, review papers, and studies that do not synergize sustainability with digital technologies are excluded. In the literature review of this study, the discussion of the excluded articles is addressed, wherein an independent preliminary assessment is conducted by two researchers with at least seven years of research experience, followed by mutual discussion to reach a consensus on the exclusion of each article. This phase ultimately reduces the selection to 72 articles. Afterward, independent data coding and comparative analysis are performed. To ensure the integrity and impartiality of data extraction, these two researchers independently read all articles thoroughly and coded the data from each study.

These data include various details, such as bibliographic information, methodology, digital technologies examined, areas of concern, and their sustainability concepts in construction. The derived datasets are independently compared to resolve discrepancies and reach consensus on themes and findings. This comparison reinforces an accurate synthesis of the literature and ensures that the results are replicable and verifiable. Finally, an analytical synthesis is conducted to summarize the current state and potential future of digital technologies in construction sustainability.

Findings

- Prominent Digital Technologies in Construction Sustainability

Through a content review of 72 articles in the literature on construction sustainability, the digital technologies that are frequently referenced and thoroughly examined have been collected. Some digital technologies have received special attention in the literature, such as Building Information Modeling (BIM) and the Internet of Things (IoT), while others have not been investigated in relation to sustainability.

1. Distribution in the literature of key digital technologies for construction sustainability from 2020 to the present shows that Building Information Modeling is the most prolific digital technology in the sustainability literature, with over 10 research articles published between 2021 and 2022. This is attributed to the role of BIM as a shared platform and tool for integrating other digital technologies at various stages of the construction life cycle. Studies related to BIM and sustainability in construction processes have seen a continuous increase since the advent of BIM, traversing the design, construction, operation, and maintenance life cycle stages.

This indicates the critical role of BIM in enhancing sustainability through collaboration, visualization, and optimization. The Internet of Things, utilizing sensors and actuators, is widely discussed in the literature as essential for collecting data relevant to sustainability. Studies show that IoT is used for monitoring and controlling energy consumption in buildings, optimizing resource utilization, and enhancing safety on-site, all of which facilitate informed decision-making regarding sustainability issues. Big Data also represents an important digital technology that leverages the vast amounts of data generated throughout the project life cycle by the IoT and other sources. There is a strong relationship between Big Data and the IoT in the current body of knowledge, as both concepts are often discussed together in studies on optimization, environmental assessments, and risk and safety management. The usage of Artificial Intelligence and Machine Learning in sustainability is gradually increasing. Their ability to process vast amounts of heterogeneous data using computational power to extract insights for sustainable decision-making is critical for effectively improving construction processes.

Other notable digital technologies in construction sustainability include Virtual Reality (VR) and Augmented Reality (AR). Studies regarding VR and AR highlight their roles in construction planning, where these digital technologies can be employed to simulate interactive experiences and explore sustainability scenarios such as energy-efficient facilities and user comfort. VR and AR technologies are described in the existing literature as tools for optimizing and visualizing early design, promoting a deeper understanding of sustainability features and enhancing commitment to sustainable outcomes. Drones represent another category of digital technologies that are increasingly used in construction for mapping, inspection, and monitoring. In the literature on construction sustainability, the application of drones in hazard identification, safe work processes, and waste reduction has been discussed. Cloud computing has also been recognized for its potential to provide centralized platforms for information management, communication, and collaboration throughout the project life cycle in relation to construction sustainability.

Based on our review of the literature, the digital technologies most relevant to sustainability in the construction industry include Building Information Modeling, the Internet of Things, Artificial Intelligence, Machine Learning, Virtual Reality, Augmented Reality, drones, and robots (Figure 1).

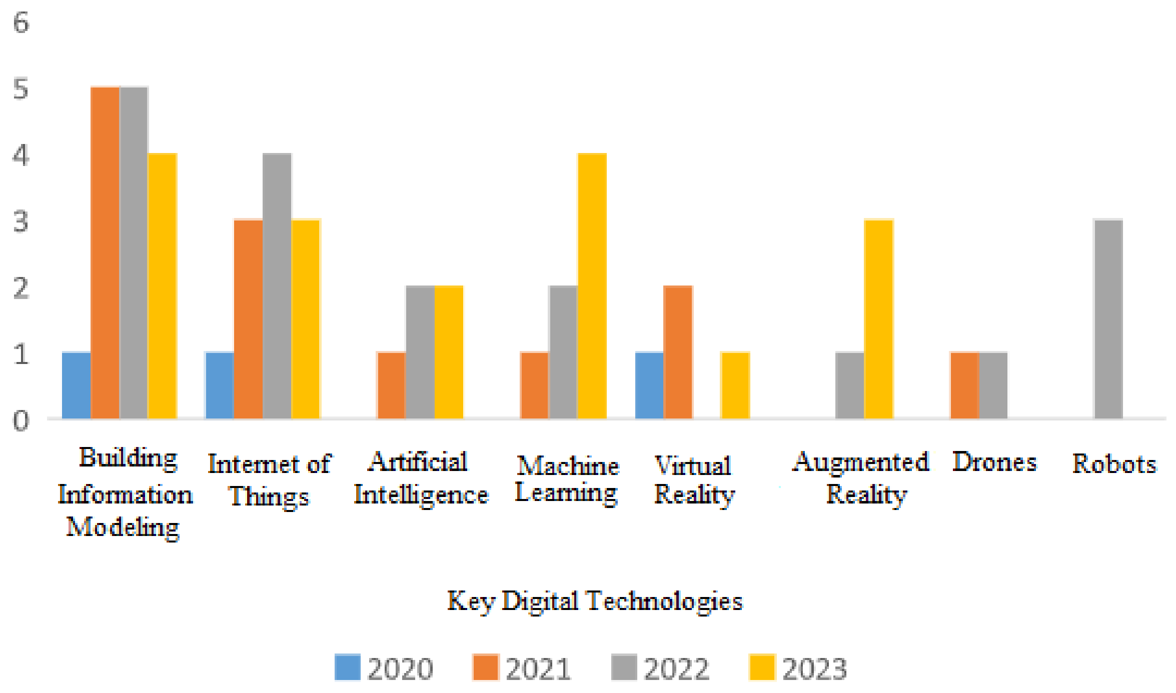

Figure 1: Distribution of Key Digital Technologies for Construction Sustainability in the Literature from 2020 to 2023

Application of Digital Technologies in Construction Sustainability

In examining the application of digital technologies for construction sustainability, analyzing their impacts at different stages of the construction life cycle is crucial. In the design phase, recent literature indicates a growing link between digital technologies and increased sustainability. Prominent examples include Building Information Modeling (BIM) in 6D, Virtual Reality, Augmented Reality, and Artificial Intelligence for design (Gnecco et al., 2023). Six-dimensional Building Information Modeling, by incorporating considerations of time (4D), cost (5D), and sustainability (6D), such as energy performance, resource efficiency, carbon emissions reduction, and resilience process simulation, goes beyond traditional three-dimensional modeling (Gan et al., 2018). The multidisciplinary coordination process of BIM allows the integration of architectural models with structural systems, heating, ventilation and air conditioning, plumbing, and electrical systems, alongside prefabricated models. This approach enables clients to visualize the complex network of systems within a building, thereby preventing rework during the construction phase (Mirpanahi & Noorzai, 2021). BIM can play a fundamental role in enhancing the energy efficiency of new and existing buildings and reducing energy costs associated with heating and cooling. A fully digital model of a structure allows for an early understanding of its behavior before construction begins. The metaverse can contribute to sustainability by facilitating broad public participation in decision-making about more efficient resource use (Sajjad et al., 2023)... Artificial Intelligence, especially in generative design, is employed to create several sustainable design alternatives based on specific constraints and goals, focusing on reducing material consumption and optimizing energy efficiency (Caldas, 2008).

In the construction phase, blockchain, the Internet of Things, radio frequency identification, digital twins, and drones play a crucial role in advancing sustainability. The potential of blockchain lies in enhancing transparency and accountability in construction processes, while smart contracts facilitate complex agreements and compliance with sustainability standards. They can streamline procurement processes, improve supply chain management, and facilitate more efficient project management. The role of the Internet of Things in sustainable construction is growing, focusing on the collection and real-time monitoring of data. IoT devices, such as sensors, are used to track resource usage and environmental conditions (Zhao et al., 2023)... thereby aiding in resource optimization and energy consumption reduction. IoT devices can be employed to enhance incident management, improve coordination of emergency responses, enhance service quality, and reduce operational costs in all areas related to infrastructure. The IoT infrastructure, as a by-product, allows for efficient planning of maintenance activities with coordination of tasks between service providers and users of these infrastructures and facilities. Radio frequency identification systems, one of the powerful IoT technologies, are widely used for effective logistics management, contributing to the reduction of the carbon footprint of construction activities by enabling precise tracking of materials, tools, and critical equipment. RFID systems help minimize losses, reduce waste, and ensure that materials are sustainably sourced and used (Rao et al., 2022).

Drones, commonly known as unmanned aerial vehicles, are increasingly utilized in construction for various tasks such as site surveys, monitoring, and inspection. They provide a unique advantage for overseeing construction activities, enabling better resource management, and ensuring compliance with environmental and safety regulations (Sajjad et al., 2023). In the operation and maintenance phase, human-robot collaboration signifies a shift towards automation, increased efficiency, and sustainability. In this context, human-robot collaboration is not about replacing human workers but enhancing their capabilities and safety. Robots are used for tasks such as cleaning, maintenance, monitoring, and inspection, reducing the workload of human staff, increasing accuracy, and enhancing safety, especially in hazardous environments. Meanwhile, blockchain improves material traceability and ensures informed decision-making for material reuse and recycling (Wu et al., 2023).

The Landscape of Digital Technologies in Construction Sustainability

Digital technologies encompass several advancements and reforms in construction value chain processes, enhancing efficiency and productivity. The opportunities for adopting these technologies to streamline production, construction, and sustainable operation in the industry are substantial. From the analysis of the literature, it was found that the driving themes in the landscape of digital technologies for sustainability are related to integration and collaboration.

Integration and Collaboration

The task of maintaining profitability while achieving cleaner, low-carbon construction processes and greener, safer workplaces requires extensive engagement, participation, and support from stakeholders. To achieve this goal, there is a need to enhance collaboration within and throughout the life cycle of various buildings. Digital technologies facilitate collaboration among stakeholders involved in the construction process by creating effective communication and information-sharing. For example, cloud-based platforms, project management software, and collaborative tools enable real-time collaboration, document sharing, and coordination among architects, engineers, contractors, and sustainability consultants. This collaboration increases the integration of sustainability considerations into projects, leading to more informed decisions and improved sustainability outcomes. Furthermore, digital technologies facilitate the integration of new and existing systems and processes to enhance sustainability outcomes. For instance, integrating Building Information Modeling with energy modeling software allows for automated energy analysis and clash detection.

Optimization, Simulation, and Decision-Making

Making informed decisions in a timely manner contributes to the efficient and cost-effective design and construction of sustainable projects. For example, sustainability analysis tools enable more informed decisions by analyzing multiple design options and identifying sustainable alternatives. These assessments assist professionals at various stages in determining the implications of their building designs for performance and environmental efficiency. To enhance sustainability, digital technologies allow for optimization through the exploration of several design possibilities and the assessment of social, environmental, and energy performance using Building Information Modeling. This aids in the identification of the most sustainable design solutions, reducing material waste, energy consumption, and environmental impacts.

Monitoring and Control

Some studies have explored mechanisms for monitoring sustainable aspects, such as greenhouse gas emissions associated with construction, using digital technologies that enable real-time tracking and monitoring of work progress and building performance (Zhang et al, 2022). Building management systems, IoT sensors, digital twins, and data analytics platforms collect data related to energy consumption, indoor environmental quality, occupancy patterns, and equipment performance. This data helps identify inefficient areas, specify maintenance needs, and optimize resource use, resulting in energy savings, improved occupant comfort, and reduced environmental impacts (Wei et al, 2022).

Challenges of Applying Digital Technology in Construction Sustainability

The deployment of digital technologies for construction sustainability faces multiple challenges at various stages of the project life cycle. First, accurate data and information are essential for conducting sustainability analyses during the design and planning phases of projects. However, the current challenge is the quality of data and the availability of construction products and services, making it difficult to fully benefit from the potential applications of digital technologies (Qi et al., 2021). Data related to material properties, energy consumption, and environmental impacts may not readily be available or standardized, complicating accurate assessments of sustainability performance. Standardized protocols, formats, and data exchange mechanisms that ensure data quality and compatibility across different digital tools and platforms are still largely underdeveloped and unable to comprehensively address all aspects of sustainability considerations in the construction industry (Petrov and Hakimov, 2019).

At the same life cycle stage, various digital tools and applications, such as Building Information Modeling, Geographic Information Systems, energy modeling software, and sustainability analysis tools, generate different types of data in various formats and qualities (Yevu et al., 2021). At different stages of the life cycle, collecting real-time data from various sources, such as sensors and equipment, and integrating it into a cohesive system can be complex (Meng et al., 2021).

Another key challenge is the integration of sustainability parameters, including balancing conflicting design goals and ensuring compatibility with existing systems within digital frameworks. The deployment of digital technologies for sustainable construction requires expertise in certain unconventional areas of construction, and given the existing skill gaps in the construction workforce, finding such expertise can be difficult (Meng et al., 2021). Many benefits of deploying digital technologies for construction sustainability point to reduced labor costs for organizations through the use of automated workflows. However, this can lead to job losses and worker segmentation, which may in turn result in resistance to changes stemming from a lack of training, awareness, and engagement. There is a need to develop innovative and diverse educational approaches, but it is unclear how these challenges have been addressed in the current literature (Malagnino et al., 2021). The introduction of both digital technologies and sustainable practices in the construction industry is emerging, but it is on the rise. Therefore, informed planning and capital investment to enhance industry skills and manage behavioral changes with necessary actions are needed, which may fully divert from existing supply chain operations. Additionally, at the core of digital technologies for construction sustainability is the need for collaboration and stakeholder engagement. However, due to the extensive and fragmented nature of stakeholders throughout the construction project life cycle—including designers, contractors, facility managers, maintenance personnel, and residents—tracking and fostering effective collaboration can be challenging (Wang et al., 2020). This challenge arises from the lack of efficient communication channels, reluctance to share and transfer knowledge and information, and the failure of parties involved to cultivate sustainable initiatives. Other challenges relate to compliance with regulatory requirements and ensuring data security, protection, and issues associated with the deployment of digital technologies. Given the long-term monitoring of the performance of sustainability features and systems throughout the life cycle of a building or infrastructure, the establishment of trust and efficient systems is vital. Ensuring the continued optimal performance of digital systems, maintaining modern sustainable practices during renovation or retrofitting, and monitoring changes in building performance requires continuous data collection, analysis, and stakeholder engagement, which can be costly (Love and Matthews, 2019).

Discussion and Conclusion

This study reviews the current applications of digital technologies in promoting construction sustainability and highlights opportunities for future research and innovations. It achieves this by adopting a systematic literature review and content analysis to identify digital technologies used in relation to construction sustainability. The findings show that Building Information Modeling, the Internet of Things, digital twins, smart robotics, and big data have emerged as prominent technologies over the past five years.

The contribution of this study lies in providing a comprehensive perspective on digital technologies for construction sustainability throughout the construction life cycle. Its theoretical contribution within the framework of sustainable construction technologies identifies gaps in the existing literature and suggests new pathways for the effective deployment and implementation of these technologies. It also enhances knowledge about how digital technologies can be applied in various construction scenarios to achieve sustainable outcomes. For the industry and practice, this study provides insights into the challenges of deploying digital technologies for construction sustainability, enabling practitioners to anticipate and manage risks before implementation. Policymakers can be informed about the prospects of digital technologies and their applications at various stages of construction. This can guide the development of policies and regulations suitable for efficiently advancing digital technologies to achieve sustainability in the industry.

The findings of this critical review of the themes, perspectives, challenges, and applications of digital technologies in enhancing construction sustainability provide a complete picture of current research activities and highlight relevant gaps and future research needs. These future research needs reflect the identified untapped potential of analyzing and assessing future impacts presented in the existing literature, which is described below.

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