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Exploration of Digital Transformation of Construction under Low-Carbon Background

Pengzhen Wang*
Henan Province Construction Group Corporation, Ltd, Zhengzhou, China
**Corresponding Author*

Abstract: Against the backdrop of the escalating global climate crisis and a deepening consensus on sustainable development, reducing carbon emissions and achieving carbon neutrality have become a focus of international attention. As a major source of carbon emissions, the carbon reduction measures of construction companies are of significant strategic importance in achieving the "dual carbon" goal. This paper focuses on the construction phase, exploring how digital transformation can achieve energy conservation and emission reduction. First, it analyzes the inherent logical connection between digitalization and decarbonization. Then, it elaborates on the specific applications and value of digital technologies such as Building Information Modeling (BIM), Internet of Things (IoT), and big data in reducing material waste, improving energy efficiency, and optimizing construction organization. Research shows that digital transformation can effectively empower the refined management of construction and is a core driving force for achieving low-carbon goals. Finally, this paper proposes corresponding countermeasures and suggestions to address practical difficulties and contribute to the sustainable development of the industry.

Keywords: Low-Carbonization; Digital Transformation; Smart Construction; Building Construction; BIM

1. Introduction

As one of the world's largest carbon emitters, China has announced to the world the ambitious goal of "peaking carbon dioxide emissions before 2030 and striving to achieve carbon neutrality before 2060". According to the "China Building Energy Consumption and Carbon Emission Research Report (2024)", building-related activities generated 5.13 billion tons of carbon emissions in 2022, accounting for 48.3% of the total carbon emissions in the country [1]. Based on these data, we can conclude that the construction industry is crucial to achieving China's dual carbon goals of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060. Promoting the low-carbon transformation of the construction industry is not only crucial for achieving China's climate goals, but also crucial for ensuring the sustainable development of the industry [2]. In terms of construction and building industry construction, it mainly includes building operation and building construction. Building construction includes building material production, transportation and construction installation. Improving total factor carbon productivity (TFCP) is an important way to achieve low-carbon transformation (LCT) in the construction industry. Traditional construction mode has problems such as labor intensity, environmental damage and low efficiency, large amount of waste, noise and dust pollution in terms of material management, energy consumption, construction efficiency and waste disposal, which are contradictory to the requirements of low carbon.

Existing research shows that the digital transformation of enterprises has a significant promoting effect on carbon emission reduction. Digital technology provides a new solution for refined, intelligent and green construction management. Through digital transformation, enterprises can achieve structural optimization, resource integration, efficiency improvement and benefit increase, thereby reducing carbon emissions. Zhang et al. pointed out that digital transformation helps to reduce the carbon emission intensity of enterprises. Energy conservation and emission reduction are mainly achieved by improving internal control efficiency and promoting green technology innovation of enterprises [3]. Emerging technologies such as big data, artificial intelligence, blockchain, cloud computing, and the Internet of Things are constantly emerging. Kazemeini et al. proposed a PPO algorithm based on deep reinforcement learning (DRL) to optimize the environmental impact of building pavement management strategies [4]. Lewis-Brown E et al. constructed a new low-carbon management system and used carbon accounting methods to reduce greenhouse gas emissions by analyzing and judging carbon emissions in the atmosphere [5]. Achieving comprehensive digital transformation of the construction industry is one of the important ways to achieve high-quality and low-carbon development of the construction industry.

This paper aims to systematically explore the mechanism and practical path of digital transformation in promoting energy conservation and emission reduction in the construction stage. The structure of the full text is as follows: Chapter 2 analyzes the inherent logical relationship between digitalization and decarbonization and establishes the theoretical foundation; Chapter 3 is the core argument, focusing on the specific application value of digital technologies such as BIM, Internet of Things, and big data in material management, energy consumption control, and construction optimization; Chapter 4 proposes a system of countermeasures to promote digital transformation in response to practical difficulties. Through the above research, this paper hopes to provide construction companies with an operable digital transformation solution, enhance the ability of refined construction management, and thus provide effective support for the industry to implement the "dual carbon" goal.

2. The Intrinsic Connection between Digitalization and Decarbonization

2.1 The Core Concepts of Digital Technology and Decarbonization

Decarbonization of building construction refers to the construction mode that minimizes the negative impact on the environment by adopting new technologies, new processes, new materials and scientific management during the construction phase of building projects. Its core objective is to improve energy efficiency and resource efficiency. Digital technology covers four core technologies: cloud computing, big data, artificial intelligence and Internet of Things. Cloud computing provides a configurable computing resource sharing pool through the network, and enterprises and individuals do not need to build complex data centers, which reduces operating costs and energy consumption. Big data technology can collect, store, analyze and mine massive amounts of data, providing data support for decision-making in various industries. Artificial intelligence uses machine learning, deep learning and other technologies to achieve intelligent decision-making and automated control. Internet of Things connects objects in the physical world to the Internet through sensors, radio frequency identification and other technologies, realizing information interaction between things and between people and things [6]. Digital technology can mainly show three characteristics. First, it is data-driven. Real-time data acquisition and analysis capabilities optimize decision-making efficiency, such as smart grids reducing energy waste by 15% to 30% through dynamic load forecasting [7]. Second, integration. The application of Artificial Intelligence & Internet of Things (AIoT) in the building sector has reduced energy consumption of building automation systems by 40% [8]. Third, scalability. Carbon trading platforms supported by blockchain technology have greatly improved the efficiency of carbon emission rights transfer.

2.2 Analysis of the Double Helix Driving Model and its Internal Mechanism

Early academic research did not directly study the relationship between digitalization and decarbonization. Instead, it reflected this relationship through specific applications of digitalization in the field of carbon emissions. Only in recent years has it gradually been conceptualized into a concrete research subject. This paper explores in detail the interaction mechanism between digitalization and decarbonization, arguing that digitalization and decarbonization are not simply a tool-to-purpose relationship, but rather like the double helix structure of DNA, intertwined, mutually driving, and co-evolving. Digital transformation can collect and sense carbon emission-related data through IoT sensors, integrate and visualize data through BIM platforms, and conduct subsequent data analysis and insights using big data algorithms. Under these digital processes, carbon flow can be basically measured, reported, and verified, providing accurate scientific basis for low-carbon decision-making. This is the first driving helix. The second driving helix is to minimize carbon emissions through process optimization. BIM-based collaborative design, prefabricated production, and lean construction can achieve carbon emission process reengineering and collaboration, thereby reducing resource misallocation and waste, lowering energy and material consumption, and suppressing carbon emissions at the source. Digital transformation fundamentally drives the low-carbon transformation of building construction through two main paths: data intelligence and process optimization. Digital technologies, such as the Internet of Things (IoT), provide the "nerve endings" of the construction process, enabling real-time monitoring of energy consumption and material usage. Big data and AI constitute the "decision-making brain," performing data analysis, prediction, and intelligent scheduling. BIM-based construction simulations can verify and optimize construction plans, site layouts, and tower crane operation paths in a virtual environment before construction begins, avoiding substantial carbon emissions caused by rework, conflicts, and inefficient organization. Digital platforms break down information silos between design, procurement, and construction, facilitating more efficient collaboration and enabling the efficient implementation of low-carbon construction models such as "Engineering, Procurement, and Construction (EPC)" and "Industrialized Building (Prefabrication)."

3. Application and Value Realization of Key Digital Technologies in Construction Carbon Reduction

This chapter will focus on the construction phase, deeply analyze the specific application scenarios of key digital technologies such as BIM, IoT, and big data in "energy saving, material saving, and efficiency improvement", and demonstrate their carbon reduction value and realization path through case studies or data (Figure 1).

3.1 BIM Technology

Building Information Modeling (BIM) technology, as the "digital twin" model of a project, has the core value of "trial before construction" to avoid waste from the source. BIM technology uses functions such as three-dimensional visualization, data integration and parametric modeling to simulate and analyze the energy consumption, lighting and ventilation of buildings in the architectural design stage, optimize architectural design schemes and improve the energy-saving performance of buildings [9].

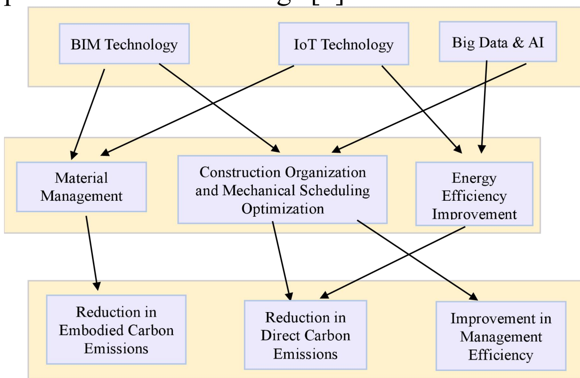

Figure 1. Application Scenarios and Value Paths of Key Digital Technologies Driving Carbon Reduction in Construction.

3.1.1 Application scenario 1: in-depth design and collision detection

Before construction, in-depth collision detection and comprehensive optimization are carried out on the building, structure and electromechanical pipelines. This directly reduces rework in the construction stage. According to relevant cases, it can effectively avoid 5%-10% material loss and mechanical waste caused by design conflicts, thereby significantly reducing implicit carbon emissions.

3.1.2 Application scenario 2: model-based prefabrication

Using BIM models to generate component processing drawings, drive the factory to accurately cut materials and produce, and then transport them to the site for assembly. Achieving "factory-style on-site operations" involves transferring wet and energy-intensive tasks from the construction site to a controlled factory environment. Processing precision can reach the millimeter level, material loss can be reduced to below 2%, and on-site construction waste and dust are also reduced.

3.1.3 Application scenario three: 4D/5D construction simulation

By linking the BIM model with construction progress (4D) and cost (5D), the entire construction process can be dynamically simulated. This optimizes the construction sequence, site layout, and the operating paths of large machinery (such as tower cranes), reducing machinery idleness, repetitive handling, and ineffective movement, directly reducing direct carbon emissions related to fossil fuel consumption.

3.2 IoT Technology

IoT is a product of the rapid development of information technology. It greatly enhances people's ability to interact with the material world and promotes the sustainable development of the economy and society [10]. IoT technology equips construction sites with "sensory nerves", making carbon emissions online, visible and controllable, and realizing carbon flow monitoring and optimization based on real-time perception.

3.2.1 Application scenario 1: real-time monitoring of construction energy consumption

Smart meters and fuel consumption sensors are installed on temporary power lines and large machinery to collect energy consumption data in real time. This enables accurate metering of major energy-consuming equipment, identifies abnormal energy consumption and "carbon leakage points," such as unnecessary standby power consumption during non-operating nighttime hours, and provides data tools for energy-saving interventions.

3.2.2 Application scenario 2: intelligent material management

Using RFID tags or QR codes on major building materials such as steel bars and concrete, combined with weighbridge sensors, tracks the entire process of materials from arrival, requisition, to installation. This effectively curbs material loss and over-requisition, achieving refined management of "requisitioned materials within limits." Real-time tracking of leftover concrete allows for its reuse, reducing material waste.

3.3 Big Data and Artificial Intelligence

Big data and AI serve as the "decision-making brain" of the project, enabling predictive decision-making based on data intelligence, shifting from post-event analysis to pre-event prediction, and achieving proactive control of carbon emissions.

3.3.1 Application scenario 1: energy demand forecasting based on machine learning

By integrating historical energy consumption data, weather forecasts, and construction plans, an AI model is trained to predict the total electricity load at the construction site for the next 24 hours. This provides a basis for intelligent scheduling of temporary power consumption. For example, it can automatically adjust non-critical processes during peak electricity consumption periods or optimize the operating times of high-power equipment such as tower cranes and elevators to achieve peak shaving and valley filling, thereby improving overall energy efficiency.

3.3.2 Application scenario 2: optimization of coordinated scheduling of construction machinery

By utilizing operations research algorithms, and comprehensively considering the logical relationships and machine locations of multiple tasks such as earthwork excavation, concrete pouring, and component hoisting, an optimal machine scheduling scheme is generated. Minimizing the total operating distance and waiting time of the machinery directly reduces diesel and gasoline consumption, which is one of the most effective ways to reduce direct carbon emissions.

3.4 Technology Integration

The carbon reduction capabilities of a single technology are limited; its greatest value lies in the integration of BIM, IoT, and big data, forming a digital twin-driven collaborative platform for carbon reduction. Real-time IoT data drives BIM model updates, ensuring consistency with the physical site. The BIM model provides precise spatial and semantic context for IoT data and AI algorithms. AI algorithms analyze, simulate, and optimize based on comprehensive data in the digital space, feeding back optimal instructions to the physical site. This achieves a leap from "single-point energy saving" to "system energy saving," enabling comprehensive, end-to-end, and adaptive refined management of construction carbon emissions.

4. Practical Challenges and Countermeasures in Promoting Digitalized Construction and Carbon Reduction

Currently, the application of digital technology in the green and low-carbon field still faces several challenges. Firstly, the technological and cost barriers are high. In data processing, with the continuous growth of data volume, data processing speed and storage capacity face challenges. In artificial intelligence algorithms, the accuracy and stability of some algorithms need improvement. In IoT technology, the interconnection and compatibility issues between devices have not been fully resolved. Secondly, small and medium-sized enterprises (SMEs) find it difficult to afford the initial investment. Thirdly, there is a shortage of talent, particularly those with combined expertise in both construction and digitalization. Furthermore, data is not interoperable between different software and systems, lacking unified standards and creating data silos. Finally, management model transformation is difficult, with reliance on traditional paths, requiring the reshaping of organizational structures and business processes.

To address these issues, this paper proposes several suggestions: At the government level, it is recommended to strengthen policy guidance and financial subsidies, and formulate data exchange and carbon emission standards; at the industry level, it is recommended to establish industry-level platforms, promote successful cases, and organize talent training; at the enterprise level, it is recommended to formulate a phased digital transformation strategy, starting with pilot projects, and focusing on cultivating and attracting multi-skilled talent.

5. Conclusion

Against the backdrop of the global convergence of low-carbon transformation and the digital wave, promoting digital transformation in the construction phase has become a key path to achieving carbon reduction and sustainable development in the construction industry. This paper systematically explores the inherent mechanisms, technological pathways, and practical strategies of digital transformation in promoting energy conservation and emission reduction during the construction phase, drawing the following main conclusions:

First, there is a synergistic "double helix" relationship between digitalization and low-carbonization. Digitalization not only provides technological tools for low-carbonization but also reshapes construction management models through data intelligence and process optimization, achieving precise measurement, process optimization, and source control of carbon emissions, forming a new carbon reduction paradigm centered on data-driven approaches.

Second, key digital technologies, represented by BIM, IoT, big data, and AI, have significant carbon reduction value in the construction phase. BIM technology avoids waste at the source through "trial before construction"; IoT technology enables real-time perception and precise control of energy consumption and materials; and big data and AI improve overall energy efficiency and machinery scheduling efficiency through prediction and optimization. The "digital twin" platform formed by the integration of these three technologies further promotes construction carbon management from "single-point energy saving" to "systematic energy saving." Third, despite the enormous potential of digital transformation, current practices still face multiple challenges, including high technology costs, a shortage of multi-skilled personnel, a lack of data standards, and outdated management models. Collaboration among government, industry, and enterprises is needed, employing multi-dimensional measures such as policy guidance, platform co-construction, standard setting, and talent development to jointly build a healthy ecosystem for promoting digital carbon reduction in construction.

Looking ahead, with the continuous maturation and deepening integration of digital technologies, construction will gradually achieve a fundamental shift from "experience-driven" to "data-driven," and from "extensive management" to "refined low-carbon" practices. The technological path and countermeasures proposed in this paper can provide theoretical reference and practical guidance for construction companies to promote digital transformation and achieve "dual-carbon" goals. Future research can further focus on the construction of integrated digital technology platforms, methods for tracking the entire carbon footprint chain, and the quantitative assessment of transformation benefits, continuously promoting the high-quality development of the construction industry towards green, intelligent, and low-carbon directions.

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