

Article

Research on the Transformation of Intelligent Construction under the Background of Dual Carbon

Xinyang He ^{1,*}¹ Hainan Vocational University of Science and Technology, Haikou, China

* Correspondence: Xinyang He, Hainan Vocational University of Science and Technology, Haikou, China

Abstract: The construction industry stands as one of China's primary carbon emission sources, accounting for approximately 40% of the nation's total carbon emissions. Under the strategic goals of "carbon peaking and carbon neutrality," the high energy consumption and emission characteristics of traditional construction models have become a critical bottleneck hindering the industry's sustainable development. Meanwhile, next-generation information technologies---such as artificial intelligence, the Internet of Things, digital twins, and construction robots---are advancing rapidly. As the core direction of digital transformation in the construction sector, intelligent construction offers a novel technical pathway to address the industry's carbon emission challenges. However, systematic research on the integration of intelligent construction with the dual-carbon goals remains insufficient, and the intrinsic mechanisms and practical approaches of technology-driven carbon reduction require further exploration. To bridge this critical gap, this study comprehensively investigates the transformative potential of intelligent construction methodologies in facilitating a low-carbon paradigm shift. By analyzing the lifecycle of building projects, from architectural design and material procurement to on-site execution and facility management, we identify key areas where digital interventions yield the most significant environmental benefits. Furthermore, the research evaluates the socio-economic barriers to adopting these advanced technologies, proposing a strategic framework that aligns regulatory incentives with technological innovation. Ultimately, this paper provides actionable insights for policymakers and industry stakeholders, demonstrating that the synergistic application of smart technologies is indispensable for achieving long-term ecological sustainability and operational efficiency within the modern built environment.

Keywords: intelligent construction; digital transformation; low-carbon transition; energy conservation; carbon neutrality

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1. Introduction

Under the framework of the dual carbon goals, the construction industry faces an urgent need to transition from traditional high-carbon models to innovative approaches that emphasize low-carbon, green, and intelligent development. This transformation is essential for achieving sustainable development and addressing the challenges posed by carbon neutrality. Green buildings, as a cornerstone of this shift, are defined as construction projects that prioritize energy efficiency and environmental protection. These buildings are designed to enhance eco-friendliness, promote health and comfort, and foster a harmonious relationship between humans and nature. By integrating advanced technologies, green buildings aim to reduce environmental impact while maintaining high standards of functionality and livability.

Intelligent construction plays a pivotal role in this transition, leveraging cutting-edge tools such as CAD for precise drafting, BIM modeling for comprehensive project visualization, IoT technologies for interconnected systems, and smart engineering solutions for optimized operations. These technologies enable seamless management across the entire lifecycle of construction projects, significantly contributing to energy

conservation and emission reduction. For instance, BIM modeling allows for detailed simulations of energy usage, enabling architects and engineers to identify inefficiencies and implement corrective measures. Similarly, IoT technologies facilitate real-time monitoring of energy consumption and environmental conditions, ensuring that buildings operate within sustainable parameters. The integration of these tools not only enhances operational efficiency but also aligns construction practices with broader environmental objectives.

The convergence of traditional engineering methods with intelligent construction represents a transformative trend in the industry [1–3]. This shift is driven by the need to address the limitations of conventional construction practices, which often rely on resource-intensive processes and outdated evaluation systems. Intelligent construction introduces a paradigm that emphasizes adaptability, precision, and sustainability, offering a viable pathway for the industry's evolution. However, the transition is not without challenges. The adoption of smart construction methods requires a comprehensive understanding of new technologies and their applications, as well as the development of market evaluation systems that accurately reflect the benefits of these innovations. Additionally, stakeholders must navigate the complexities of integrating intelligent solutions into existing workflows, ensuring that the transition is both efficient and effective.

To facilitate this transformation, it is crucial to establish clear objectives that align with the principles of low-carbon development. These objectives should serve as a roadmap for the industry, guiding efforts to reduce energy consumption and minimize environmental impact. Big data processing technologies play a central role in achieving these goals, offering powerful tools for analyzing and optimizing construction processes. By harnessing the capabilities of big data, stakeholders can gain valuable insights into energy usage patterns, identify areas for improvement, and implement targeted strategies for emission reduction. For example, data analytics can be used to predict the energy performance of buildings under various scenarios, enabling proactive decision-making and resource allocation.

Moreover, the integration of big data technologies into construction practices supports the development of intelligent systems that can adapt to changing conditions and requirements. These systems enhance the industry's ability to respond to environmental challenges, ensuring that construction projects remain aligned with sustainability objectives. The use of big data also facilitates collaboration among stakeholders, enabling the sharing of information and best practices across the industry. This collaborative approach fosters innovation and accelerates the adoption of intelligent construction methods, paving the way for a more sustainable future.

In conclusion, the transition to low-carbon, green, and intelligent construction is a critical step for the industry in achieving the dual carbon goals. By prioritizing energy efficiency, environmental protection, and technological innovation, stakeholders can drive meaningful progress toward sustainable development. The integration of advanced tools such as CAD, BIM, IoT, and big data processing technologies offers a robust framework for this transformation, enabling the industry to overcome traditional limitations and embrace a more sustainable and intelligent future. As the construction industry continues to evolve, it is essential to maintain a focus on these principles, ensuring that progress is both impactful and enduring.

2. Design Phase

1. The planning and decision-making phase is a critical stage in project development, where a systematic feasibility study is conducted to ensure the project's alignment with sustainable and innovative goals. This involves preparing a comprehensive project proposal that emphasizes three essential dimensions: low-carbon development, green construction, and smart applications. By focusing on these areas, the evaluation process establishes a robust scientific basis for informed decision-making. Once the proposal undergoes a thorough review, the project proceeds to

approval or investment decision-making, accompanied by two pivotal assessments. The first assessment involves a preliminary calculation of the project's lifecycle carbon emissions, which serves to define clear decarbonization targets and pathways. This calculation is instrumental in setting measurable goals for reducing the project's environmental impact. The second assessment entails an in-depth analysis of smart construction technology, examining its application scenarios and implementation depth. This analysis clarifies the functional positioning and technical requirements of intelligent construction systems, ensuring their effective integration into the project. Together, these efforts create a solid foundation for achieving green and low-carbon transformation while enabling digital implementation during subsequent design and construction phases. By prioritizing sustainability and technological innovation, this phase ensures that the project is well-prepared to meet modern environmental and operational standards.

2. The field survey and smart design phase builds upon the insights gained from actual survey data to formulate a planning concept that aligns with the project's sustainability objectives. Specialized designs are developed to address key areas such as energy conservation, material efficiency, water conservation, carbon reduction, and the selection of green materials. These designs are tailored to optimize resource use and minimize environmental impact, ensuring that the project adheres to high standards of ecological responsibility. Additionally, this phase marks the initial implementation of digital platforms, including smart construction sites, intelligent monitoring systems, and Building Information Modeling (BIM). These platforms play a crucial role in enhancing project efficiency and accuracy. For instance, smart construction sites enable real-time monitoring and management of construction activities, while intelligent monitoring systems provide valuable data on environmental and operational parameters. BIM facilitates the visualization and simulation of construction processes, allowing for precise planning and coordination. By integrating these digital tools, the field survey and smart design phase lays the groundwork for a technologically advanced and environmentally sustainable project. This approach not only improves operational efficiency but also ensures that the project meets its green and low-carbon objectives.
3. The construction drawing design and review phase is a meticulous process that ensures the project's compliance with technical, environmental, and operational standards. This phase involves a comprehensive review of construction drawings to verify their adherence to fire safety regulations, green energy efficiency criteria, and other critical requirements. Additionally, the bill of quantities, bidding procedures, carbon emission calculations, and smart construction implementation plans are thoroughly examined to ensure their accuracy and alignment with project goals. Digital collaborative management systems are employed to streamline these processes, promoting energy conservation and emission reduction. By leveraging advanced big data platforms such as smart construction sites and BIM, a model database is established to optimize the use of existing materials and enhance resource efficiency. This database serves as a valuable resource for selecting green, low-carbon materials that align with the project's sustainability objectives. Furthermore, the use of digital tools effectively prevents rework and waste during later construction phases, contributing to the project's overall efficiency and environmental performance. By integrating these innovative approaches, the construction drawing design and review phase ensures that the project is well-equipped to achieve its green and smart construction goals.

3. Operation Phase

The construction phase represents a pivotal period in building projects, particularly in terms of carbon emissions. By implementing intelligent management systems such as Building Information Modeling (BIM), big data platforms, and smart engineering systems, significant progress can be made toward achieving emission reduction goals. These

systems enable efficient material allocation and resource optimization, ensuring that construction activities are carried out with minimal environmental impact. For instance, the big data processing platform facilitates the precise distribution of materials, reducing waste and enhancing resource efficiency. IoT sensors deployed at key construction sites play a critical role in monitoring essential parameters such as wind speed, temperature, humidity, structural stress, and harmful gas concentrations. When safety thresholds are exceeded, the system automatically triggers alerts and activates emergency protocols, such as suspending operations or evacuating personnel. These measures significantly reduce accident rates, particularly in high-altitude steel structure installations. Additionally, 24/7 worker health monitoring systems provide early warnings for potential incidents, minimizing workplace accidents and lowering risk-related costs. A smart weather monitoring system further enhances operational efficiency by adjusting dust control measures based on humidity variations, optimizing implementation plans to reduce energy consumption in water and electricity systems. By integrating these advanced technologies, the construction phase achieves a balance between operational efficiency and environmental sustainability, setting a new standard for modern building projects.

Traditional construction methods often face challenges such as prolonged operational cycles and inadequate resource management and coordination. Intelligent construction systems address these issues by enabling integrated control across all phases and dimensions of a project. These systems leverage sensor data collection and big data processing to intelligently manage the entry and exit of materials, labor, and equipment. This approach provides early warnings and precise maintenance, minimizing resource waste and enhancing overall project efficiency. Furthermore, clean energy sources such as wind, solar, and hydropower are utilized to support sustainable operations. Natural energy is converted into electrical power through inverters, which standardize the output as AC power compliant with grid specifications. This energy is then optimized for various applications, including small equipment charging, public lighting, perimeter water spraying for dust suppression, and corridor ventilation. These measures contribute to significant reductions in carbon emissions, aligning the project with global sustainability standards. By integrating advanced technologies and clean energy solutions, intelligent construction systems transform traditional building practices into comprehensive low-carbon operations. This innovative approach not only enhances resource efficiency but also ensures that the project meets its environmental and operational objectives, paving the way for a more sustainable future in construction.

4. Resource Utilization Phase

Upon completion of the initial phase, the resource utilization stage represents a critical juncture in advancing low-carbon smart construction methodologies [4, 5]. This phase leverages cutting-edge technologies, such as end-to-end big data processing and Building Information Modeling (BIM), to optimize resource allocation and project management. By employing BIM-based quantity calculations, project managers can accurately forecast material requirements, monitor progress, and ensure cost-effective operations. Additionally, comprehensive project progress forecasting and cost accounting enable stakeholders to maintain strict control over budgets and timelines, while quality control measures ensure that construction standards are upheld. This integrated approach not only enhances operational efficiency but also aligns with the overarching goal of achieving low-carbon smart construction. Throughout the lifecycle of a project, residual materials are meticulously sorted, refined, and either recycled or reallocated to other projects, thereby minimizing waste and promoting sustainability. The smart construction platform plays a pivotal role in this process by centralizing big data analysis, which facilitates innovative resource repurposing strategies. For instance, non-potable water resources, such as industrial wastewater and rainwater, can be treated and repurposed for applications like sedimentation processes used in greenery irrigation or for cleaning buildings post-construction. These practices significantly enhance resource efficiency and

contribute to the broader objectives of environmental conservation and sustainable development.

The final phase of low-carbon smart construction involves a thorough evaluation of its environmental and operational benefits, particularly in infrastructure projects. This phase emphasizes the alignment of energy-saving and emission-reduction outcomes with ecological conservation principles. Core values underpinning this phase include the efficient use of materials throughout the project lifecycle, the conservation of natural resources, the minimization of waste, and the promotion of material recycling. These objectives are integral to reducing carbon emissions and achieving sustainable construction practices. Key performance indicators in this phase include reductions in material consumption, resource usage, and waste generation, as well as improvements in utilization rates. The smart construction platform is instrumental in achieving these goals by enabling project acceleration, enhancing quality, and facilitating low-carbon operations. By shortening project timelines, reducing costs, and minimizing the likelihood of accidents, the platform ensures that intelligent construction meets the demands of a green transition in the low-carbon era. This phase also underscores the importance of integrating advanced technologies, such as artificial intelligence and big data analytics, to monitor and optimize construction processes. These technologies enable real-time decision-making and adaptive management, ensuring that projects remain aligned with sustainability objectives. Ultimately, this phase demonstrates how intelligent construction can serve as a model for achieving high-quality development in the context of global environmental challenges.

Under the framework of China's national carbon peaking and carbon neutrality strategy, the transition from traditional engineering practices to intelligent, low-carbon construction has become a fundamental requirement for the industry's transformation [6–8]. This shift reflects a broader trend toward sustainable development, where green and low-carbon initiatives are no longer optional but mandatory [9–11]. The construction sector is undergoing a profound transformation, characterized by the widespread adoption of green building practices and technologies [1]. For example, the coverage rate of green buildings has been steadily increasing, driven by policies and market demand [3]. Ultra-low and near-zero energy consumption buildings are being actively promoted, setting new benchmarks for energy efficiency and environmental performance [3]. Building-integrated photovoltaics (BIPV) are becoming a standard feature in modern construction, enabling buildings to generate their own electricity and reduce reliance on external energy sources [10]. Additionally, prefabricated buildings now account for a significant portion of construction projects, with on-demand prefabrication and specialized installation techniques reducing material waste and ensuring adherence to project timelines [1]. The integration of big data technology further enhances the efficiency and sustainability of construction processes [8]. By providing comprehensive statistical analyses, big data enables the seamless integration of design, construction, and operational phases into a unified smart construction model [10]. This model incorporates artificial intelligence monitoring systems, which facilitate real-time adjustments and ensure that projects remain aligned with low-carbon and high-quality development goals [11]. Collectively, these advancements illustrate how the construction industry is evolving to meet the challenges of the low-carbon era, setting a precedent for sustainable practices across other sectors [6].

5. Conclusion

Under the guidance of the "Dual Carbon" goals, traditional engineering projects are undergoing significant transformation through intelligentization, low-carbonization, and efficiency enhancement. These advancements are reshaping the construction sector, driving the adoption of innovative technologies and sustainable practices across various dimensions, including technology, management, materials, and operational systems. The integration of big data and IoT technologies is revolutionizing construction planning, smart manufacturing, and full-cycle progress management, enabling the optimization of

processes to minimize waste, reduce rework, and curtail inefficient energy consumption. This approach not only enhances resource utilization but also aligns with the broader objectives of environmental sustainability. Concurrently, the promotion of green and low-carbon building materials is gaining momentum, with increased emphasis on renewable resources and eco-friendly construction materials. These materials are being integrated into projects to reduce the environmental footprint and support the transition to sustainable construction practices. Furthermore, building equipment and energy structures are being optimized to accelerate the replacement of traditional fuel-powered machinery with electric and intelligent construction equipment, fostering a shift toward cleaner and more efficient energy use. Renewable energy sources, such as solar and wind power, are being adapted to local conditions for on-site applications, contributing to the establishment of a low-carbon construction energy system that is both resilient and adaptable. A comprehensive low-carbon management framework is being developed to ensure that carbon emission accounting, monitoring, and evaluation mechanisms are embedded into all phases of construction projects. This framework aims to create a quantifiable, assessable, and traceable low-carbon construction model, providing a robust foundation for sustainable development. The intelligent construction of infrastructure is undergoing profound transformation, characterized by greener, more intensive, and efficient practices. These advancements are not only supporting industry development but also contributing significantly to the achievement of the "Dual Carbon" goals. Moving forward, the construction sector must continue to pioneer new IT application models to address the evolving demands of the smart construction market. This includes building a robust smart construction quality supervision system capable of effectively managing increasingly complex quality factors. Additionally, the sector must focus on developing innovative solutions to meet the challenges posed by the dynamic and rapidly changing landscape of smart construction. Future research should explore the integration of advanced technologies, such as artificial intelligence and machine learning, to further enhance the efficiency and sustainability of construction processes. Investigating the potential of emerging materials and energy systems will also be critical in driving the next wave of innovation in the construction industry. By fostering collaboration among stakeholders and prioritizing sustainable practices, the construction sector can play a pivotal role in achieving global environmental goals while addressing the challenges of urbanization and infrastructure development. These efforts will not only support the transition to a low-carbon economy but also ensure the long-term resilience and adaptability of the construction industry in the face of evolving environmental and technological demands.

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