Practice of Digital Construction to Improve Construction Project Progress Management

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Abstract: *In order to solve the problems of information islands, delayed identification of progress deviations, and inefficient resource allocation in the progress management of traditional construction projects, this paper integrates Beidou high-precision positioning, BIM (Building Information Modeling), IoT sensor network and other technologies to build a management system covering the entire chain. This paper deploys Beidou positioning terminals and vibration, temperature and humidity sensors to obtain the trajectory of construction machinery, material transportation status and environmental parameters. At the same time, based on the BIM 5D model, the design drawings and construction plans are automatically associated, and the actual progress data is dynamically updated. The progress prediction model is constructed by using the LSTM (Long Short-Term Memory) algorithm to output the probability of progress deviation in the next 3 days. In addition, the Apriori algorithm is used to identify process conflicts and generate optimization suggestions in advance. This paper also builds a cloud-based collaborative platform that integrates data from multiple parties such as design, construction, and supervision to support lightweight browsing and progress comparison of BIM models. At the same time, a resource scheduling optimization engine is developed to solve multi-objective constraint problems based on a genetic algorithm (GA). Digital construction has shown advantages in construction time, resource utilization efficiency, process conflict warning accuracy, and construction quality. The average construction time of digital construction is shorter than that of traditional construction, the resource idle rate is reduced, the accuracy of process conflict warning is improved, and the construction quality inspection pass rate is as high as 100.0%. This study provides reference and reference for the digital transformation of the construction industry.*

Keywords: *Construction Engineering; BIM; LSTM; Cloud Collaboration; Construction Quality Inspection Pass Rate*

1. Introduction

The rise of digital technologies has brought revolutionary changes to construction progress management. These technologies can provide real-time and accurate data support, realize real-time monitoring, dynamic adjustment and optimization decision-making of construction progress. However, how to systematically integrate these digital technologies and build an efficient and feasible construction progress management framework is still a difficult and hot topic in current research and practice.

This paper systematically integrates a variety of digital technologies to construct an efficient and feasible construction progress management framework; verifies the effectiveness and feasibility of digital construction through simulation experiments, and provides empirical support for the digital transformation of the construction industry; conducts technical and economic analysis, and provides a decision-making reference for construction companies to implement digital construction.

This paper first introduces the background and motivation of the research; then reviews the literature and analyzes the current research status and challenges of construction progress management; then explains the construction method and implementation process of the digital construction progress management system; then verifies the effectiveness and feasibility of digital construction through simulation experiments; finally, conducts a technical and economic analysis to evaluate the investment payback period and economic value of digital construction.

2. Related Work

With the rapid development of the construction industry, the complexity and importance of construction progress management cannot be ignored, and the rise of digital technology has brought new opportunities and challenges to construction progress management. Li et al. [1] gave an overview of BIM technology and construction progress management, and summarized the problems existing in traditional construction progress management. Arefazar et al. [2] adopted a method combining literature review and expert interviews. Through a systematic literature review, key agile project management strategies were identified, and these strategies were prioritized through expert interviews, providing a framework for construction project managers to prioritize the implementation of agile strategies. Su et al. [3] compared the characteristics of various technologies and built a collaborative management system for construction progress. Parsamehr et al. [4] summarized the main challenges in construction management from the four dimensions of progress management, cost management, quality management, and safety management, and explored the application cases of BIM technology in progress, cost, quality, and safety management. In view of the problem that the existing two-dimensional construction progress management is out of touch with the real geographical environment and has a low level of informatization, Gou et al. [5] explored the application of real-life 3D technology in the construction progress management of high-speed railways, focusing on the key technologies such as the dynamic management process of construction progress, multi-scale fusion real-life 3D modeling, and multi-level progress management visualization expression, developed a prototype system, and carried out experimental analysis.

Seyman Guray and Kismet[6] evaluated the application status and development trend of VR and AR technologies in construction management research through bibliometric and descriptive analysis. Ji et al.[7] developed a construction progress management virtual simulation experiment teaching system based on BIM, which realized the three-dimensional visualization, model lightweight, progress specialization, intelligent detection, teaching scale and process collaboration of progress management experiments. Focusing on the progress of virtual simulation experiments, they analyzed the problems existing in traditional teaching, the architecture of simulation experiment systems, functional design and implementation process, and summarized the effectiveness of the experimental system in management knowledge evaluation, large-scale parallel experiments and multi-course linkage mechanism. Franz et al. [8] explored the current status of burnout among early career practitioners in the field of construction management in the United States and its influencing factors. Yuan et al. [9] discussed the concept and importance of construction progress management, the main factors affecting construction progress management, the impact of construction progress management on project cost, the exploration of key technologies and models of construction progress management, and typical cases. The aim was to reduce waste and improve resource utilization efficiency by analyzing the importance of progress management in the construction process of construction projects and its impact on project cost. Shojaei et al. [10] explored the application effect of immersive video technology in the delivery of construction management content. Existing research has explored the application of digital technology in construction progress management from multiple aspects, but most studies still focus on theoretical analysis or the application of a single technology. In actual projects, how to systematically integrate these technologies to achieve the improvement of construction progress management remains a challenge. Therefore, this paper aims to explore the comprehensive application mode of digital technology in the construction progress management of construction projects through empirical research, and propose a set of operational practical frameworks, in order to provide reference and reference for the digital transformation of the construction industry.

3. Method

3.1 Multi-source Data Fusion System

In the practice of digital construction to promote the progress management of construction projects, the multi-source data fusion system starts from the source of data collection, deploys Beidou positioning terminals and IoT sensor networks to ensure that all kinds of key information in the construction process are captured in real time and accurately. The positioning accuracy of the Beidou positioning terminal reaches 0.1 meters, and the trajectory of construction machinery is continuously tracked, providing data support for the optimization of construction scheduling and progress monitoring [11].

The IoT sensor network monitors the quality of concrete pouring through vibration sensors (sampling rate up to 200Hz) to ensure that every construction link meets quality standards. The temperature and humidity sensors closely monitor the maintenance conditions of the construction environment with a high accuracy of ±2%RH to prevent construction quality problems caused by environmental factors.

Based on data collection, the BIM 5D model has taken multi-source data fusion to a new level. Through the IFC standard, an internationally accepted data exchange format, the IoT sensor network is deeply bound to the BIM model, achieving accurate mapping of sensor IDs and BIM component properties. This means that every BIM component reflects its physical status in real time. The BIM 5D model dynamically and automatically aligns the version information of the design drawings with the construction log, ensuring that the construction team always has the latest design intent and progress information. This real-time and accurate progress data avoids misunderstandings and delays caused by information asymmetry.

3.2 Intelligent Analysis Engine

The intelligent analysis engine includes a degree prediction model and a conflict detection module to perform in-depth mining of multi-source data.

The progress prediction model adopts LSTM (network structure, through a 3-layer stacking design, combined with the Attention mechanism, to achieve efficient prediction of the construction progress. In terms of input feature engineering, the progress prediction model comprehensively considers a variety of factors that affect the construction progress, including historical work efficiency, weather index, and supply chain delay rate [12-13]. After data preprocessing and feature selection, these factors are input into the LSTM network. After complex calculation and reasoning, the final output is the construction progress prediction result $\widehat{\mathrm{Y}}$ for a period of time in the future:

$$\widehat{\mathrm{Y}} = LSTM(Attention([H, W, S])) \tag{1}$$

[H, W, S] refers to the input feature vector.

The conflict detection module uses the Apriori algorithm to detect and warn possible process conflicts during the construction process. By learning and analyzing historical data, the Apriori algorithm discovers potential associations and conflict patterns between processes and stores them in the process conflict rule library. In terms of the optimization of the Apriori algorithm, the minimum support is 0.1 and the confidence is 0.85. This means that only when the frequency of a conflict pattern in the data set reaches or exceeds 10% and its confidence (that is, the probability of the conflict pattern occurring under given conditions) reaches or exceeds 85%, it will be identified as a valid conflict pattern.

The process conflict rule library currently contains 56 typical conflict modes, such as the timing contradiction between concrete pouring and steel bar binding, the working space conflict between different types of work, etc. When the intelligent analysis engine detects the occurrence of a conflict mode matching the rule library in the actual construction process, it will immediately trigger the early warning mechanism to remind the construction team to take timely measures to adjust and optimize, so as to avoid progress delays and quality problems caused by process conflicts.

3.3 Collaborative Decision-making and Dynamic Optimization

This paper builds a cloud-based collaborative platform and a genetic algorithm resource scheduling engine to achieve real-time sharing of multi-party data and intelligent optimization of resource scheduling.

The cloud collaboration platform realizes lightweight browsing of BIM models based on WebGL technology, allowing project participants to easily view the project's 3D model through the web page without installing complex professional software. This function greatly reduces the technical threshold and promotes transparency and sharing of information. On the cloud collaboration platform, a progress comparison function is specially designed. By dynamically comparing the actual construction progress with the planned progress in the BIM model, we can intuitively understand the progress deviation, discover problems in a timely manner and take corresponding measures [14]. At the same time, the platform supports multi-party data sharing. Participants such as design, construction, and supervision can work together on the same platform to achieve seamless information connection and efficient communication. The collaborative platform architecture is shown in Figure 1:

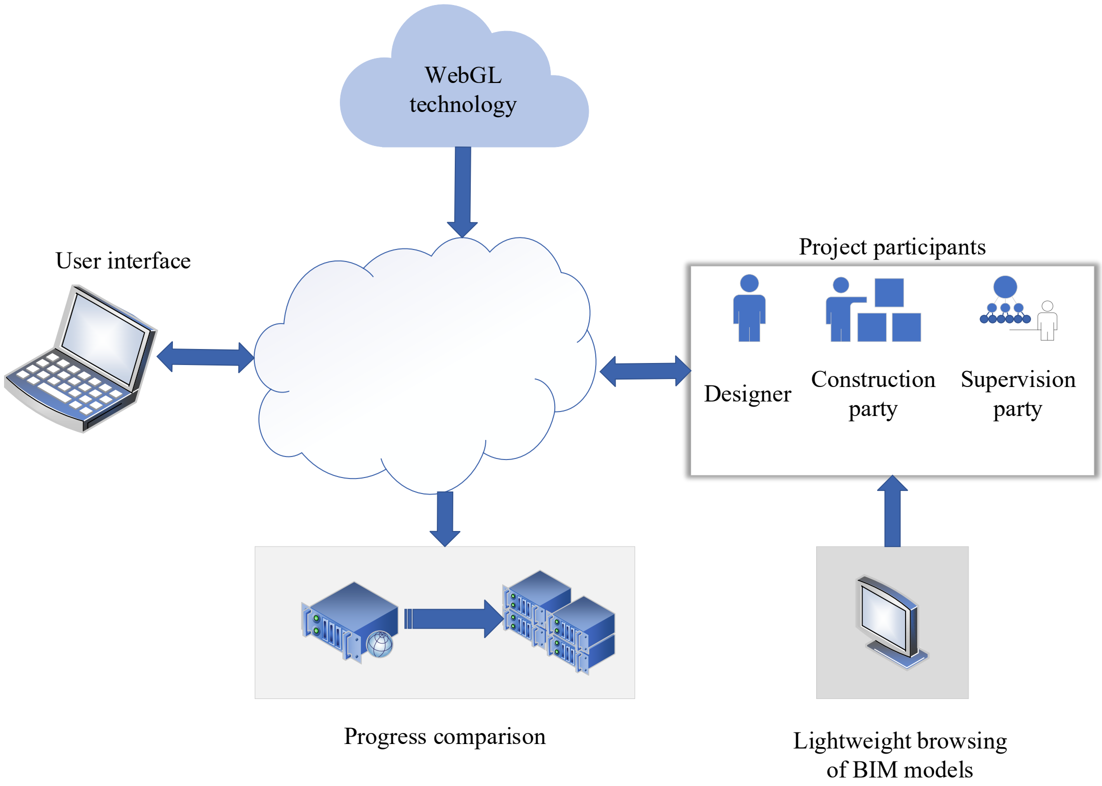

Figure 1 Platform Architecture

The genetic algorithm resource scheduling engine simulates the natural selection and genetic mechanism in the biological evolution process, and continuously optimizes the resource scheduling plan through iterative calculation. In construction projects, resource scheduling often involves multiple target constraints, such as labor division and tower crane path planning. There are often conflicts and constraints between these goals, and traditional methods are difficult to find the global optimal solution. The genetic algorithm resource scheduling engine takes into account various constraints and gradually approaches the optimal solution through continuous iteration and evolution. In actual applications, the genetic algorithm resource scheduling engine automatically adjusts the labor shift plan and optimizes the operation path of the tower crane according to the specific situation and needs of the project, thereby reducing construction costs and improving construction efficiency and safety. At the same time, the engine also has self-learning capabilities, continuously optimizing algorithm parameters and model structures based on historical data and project feedback, further improving the intelligence level of resource scheduling.

3.4 Edge Computing and Data Preprocessing

Edge computing pushes computing resources from the cloud to the edge of the network, where data is generated. In construction project progress management, this means deploying edge servers on site and transferring some data processing and analysis tasks from remote data centers to the site[15].

In terms of vibration monitoring, vibration sensors deployed on construction sites collect a large amount of data in real time. If all this data is transmitted to the cloud for processing, it will not only increase the burden on network bandwidth but also affect the effectiveness of real-time decision-making due to transmission delays. With edge computing technology, these vibration monitoring data are preliminarily processed and analyzed on the edge server at the construction site, and key information is extracted before being uploaded to the cloud.

In the process of digital construction, data preprocessing is particularly important because data sources are diverse, formats are different, and there may be missing and abnormal problems. For vibration monitoring data, data preprocessing includes data cleaning (removing outliers, filling missing values), data transformation (normalization, standardization), feature extraction (extracting key features such as vibration frequency and amplitude), etc. In the process of data normalization, the vibration data x becomes x' after normalization:

$$x' = \frac{x-\min(x)}{\max(x)-\min(x)} \tag{2}$$

min(x) and max(x) are the maximum and minimum values of the vibration data, respectively.

In the feature extraction process, the vibration frequency f and amplitude A are key features, which are extracted from the time domain signal x(t) through Fourier transform:

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \tag{3}$$

X(f) refers to the frequency domain signal; $e^{-j2\pi ft}$ refers to the complex exponential function, where j is the imaginary unit; f is the frequency; and t is the time.

Through these preprocessing operations, the quality of vibration monitoring data is improved.

4. Results and Discussion

4.1 Performance Comparison

Traditional construction progress management relies on manual records, paper documents and simple software tools (Microsoft Project), which lack the ability to update data in real time and adjust dynamically. However, digital construction in this paper uses BIM, Internet of Things and other technologies to achieve real-time monitoring and dynamic adjustment of progress plans. In order to further highlight the effectiveness of the digital construction technology proposed in this paper, this paper conducts simulation experiments in different simulated construction tasks to understand the construction time, resource idle rate, process conflict warning accuracy and construction quality inspection pass rate under the two methods. The results are shown in Figures 2, 3, 4 and 5, respectively:

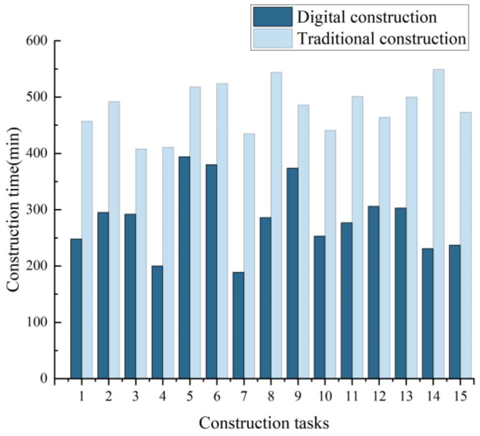

Figure 2 Construction time

As shown in Figure 2, the average time for digital construction is 284.33 minutes, while the average time for traditional construction is 480.2 minutes. It can be seen that the average construction time for digital construction is lower than the average time for traditional construction. Therefore, it can be concluded that: Digital construction has significant advantages in construction efficiency, which can effectively reduce construction time and improve the overall progress of the project. This result shows that the use of digital construction methods can not only reduce the waste of manpower and resources but also improve the transparency of information and the efficiency of collaborative work, thus bringing greater advantages to enterprises in a highly competitive market environment.

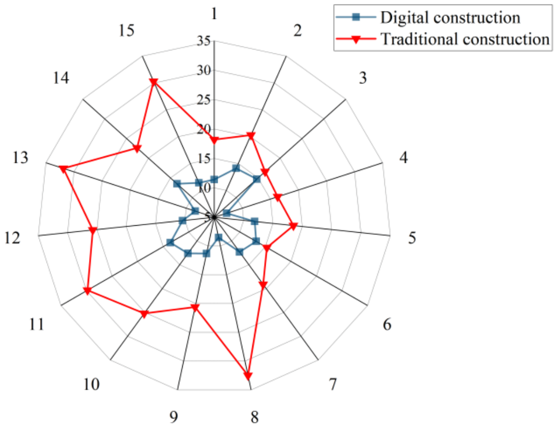

Figure 3 Resource Idle Rate

In Figure 3, the maximum idle rate of digital construction resources is 14.7% (Task 3), and the minimum is 7.2% (Task 4). The maximum idle rate of traditional construction resources is 32.5% (Task 8), and the minimum is 15.3% (Task 6). By comparing the idle rates of digital construction and traditional construction resources, it can be clearly seen that digital construction has advantages in resource utilization. The maximum idle rate of digital construction is 14.7%, while its minimum idle rate is 7.2%, which shows that among all tasks, the idle situation of digital construction resources is relatively stable and low. The resource idle rate of traditional construction shows large fluctuations. This significant difference shows that traditional construction has great limitations in resource management. Especially in some tasks, the resource idle rate will seriously affect project efficiency and cost control. Digital construction performs well in reducing the resource idle rate, which not only improves resource utilization efficiency but also helps reduce project costs and improve the overall construction management level.

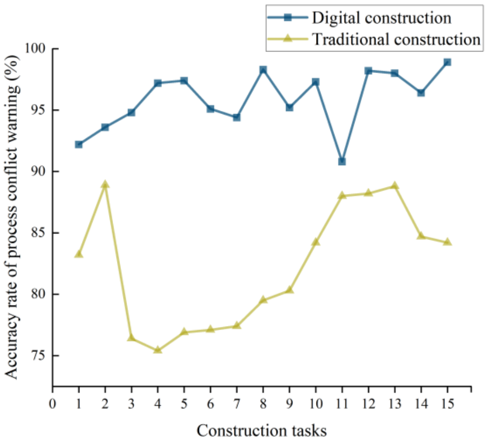

Figure 4 Process conflict warning accuracy

By comparing the process conflict warning accuracy of digital construction and traditional construction in Figure 4, it can be clearly seen that digital construction has the advantage of warning accuracy. In all tasks, the accuracy of digital construction is higher than that of traditional construction. In Task 3, the accuracy of digital construction is 94.8%, while that of traditional construction is only 76.4%, a difference of 18.4%. In Tasks 4 and 5, the accuracy of digital construction is 97.2% and 97.4%, respectively, while the accuracy of traditional construction is only 75.4% and 76.9%. This difference further highlights the effectiveness of digital construction in dealing with process conflicts. In addition, digital construction achieves an accuracy rate of 98.3% in Task 8, which far exceeds the 79.5% of traditional construction. Overall, the accuracy of digital construction generally remains above 90%, while the accuracy of traditional construction fluctuates between 75.4% and 88.9%, showing greater instability. Digital construction has excellent performance in the accuracy of early warning of process conflicts, which can not only effectively reduce risks during construction but also improve the overall management efficiency of the project.

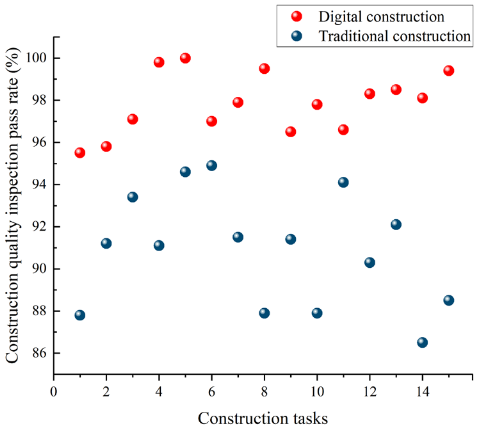

Figure 5 Construction quality inspection pass rate

As can be seen from Figure 5, digital construction is superior to traditional construction in terms of construction quality inspection pass rate. In all 15 tasks, the quality inspection pass rate of digital construction is higher than that of traditional construction, showing its effectiveness in ensuring construction quality. The highest quality inspection pass rate of digital construction reaches 100.0% (Task 5), while the highest pass rate of traditional construction is 94.9% (Task 6). This difference shows that digital construction can more effectively control and improve construction quality, reducing rework and resource waste caused by unqualified construction. In addition, in Task 4 and Task 8, the pass rates of digital construction are 99.8% and 99.5%, respectively, while the pass rates of traditional construction are only 91.1% and 87.9%, showing that digital construction can still maintain high quality standards under high pressure.

4.2 Typical Cases

Case 1 focuses on the optimization of the concrete pouring sequence. In a commercial complex project, the delay in the progress of steel bar binding seriously threatened the smooth progress of the subsequent concrete pouring work, which may lead to delays in the overall construction period and increased costs. Faced with this challenge, digital construction accurately predicts the risk of steel bar binding delay 48 hours in advance through the LSTM model, which wins valuable response time for the project team. Subsequently, the work plans of the three steel bar binding teams are reallocated using genetic algorithms, and a cross-operation strategy is implemented, effectively alleviating the schedule pressure. Ultimately, the concrete pouring work is carried out smoothly, not only shortening the construction period by 2 days but also saving 150,000 yuan in costs, which improves the overall benefits of the project.

Case 2 shows the system's outstanding performance in dealing with extreme weather challenges. In a super high-rise building project, a sudden typhoon caused serious delays in material transportation, bringing huge uncertainty to the project progress. Faced with this emergency, digital construction quickly activates the emergency response mechanism. The schedule is dynamically revised through ARIMA, fully considering the impact of extreme weather, ensuring that the revised plan is both in line with the actual situation and forward-looking. After systematic revision, the error rate of the new schedule is strictly controlled within 5%, providing a reliable basis for decision-making for the project team. With the support of the system, the project team successfully copes with the challenges of material transportation delays, ensures the relative stability of the project progress, and reduces additional losses caused by weather factors.

4.3 Technical and Economic Analysis

From a cost-effectiveness perspective, the implementation of digital construction requires a certain amount of initial investment, mainly including the deployment of sensor networks and the purchase and installation of edge servers, which together cost about 2.3 million yuan. However, the benefits brought by this investment are significant. Through accurate construction progress prediction, conflict detection, automated data processing and intelligent analysis, digital construction can reduce rework losses caused by improper planning or construction errors, and reduce reliance on manual management, thereby saving management costs. According to statistics, after implementing digital construction, the company saves about 1.8 million yuan in rework losses each year and reduces management costs by about 700,000 yuan, with a total annual savings of 2.5 million yuan, as shown in Table 1:

Table 1 Cost-effectiveness data

Item	Cost/Savings (RMB 10,000)	Description	Type
Sensor Network Deployment	150	Procurement and installation of hardware devices such as Beidou positioning terminals and IoT sensors	Initial Investment
Edge Server Purchase	80	Acquisition of equipment for local data processing and edge computing	Initial Investment
Annual Rework Savings	180	Savings from reducing rework costs due to construction errors	Annual Savings (Benefits)
Annual Management Cost Reduction	70	Reduction in management costs due to decreased manual inspections and paper-based documentation	Annual Savings (Benefits)

Based on these cost-benefit data, the return on investment (ROI) cycle of digital construction is calculated to be about 1.7 years, which means that in a relatively short period of time, the company recovers all initial investment and begins to enjoy the sustained economic benefits brought by digital construction. Therefore, from the perspective of technical and economic analysis, digital construction has high investment value and feasibility in improving the progress management of construction projects.

5. Conclusion

This paper studies the application of digital construction technology in the construction progress management of building projects, constructs an efficient and feasible construction progress management framework, verifies its effectiveness and feasibility through simulation experiments, and solves the problems of weak dynamic adjustment capabilities existing in traditional construction progress management methods. However, the environment and conditions of the simulation experiment in this paper may be different from those of actual engineering projects, so the application and promotion of the experimental results need further verification and improvement. Secondly, the implementation of digital construction technology requires a certain amount of capital and human resources, which has certain barriers for some small and medium-sized construction companies. Future research can further explore the application of digital construction technology in complex engineering projects, such as super high-rise buildings, large infrastructure, etc., as well as its integration with other technologies. At the same time, we can also focus on the application potential of digital construction technology in sustainable development, environmental protection, etc., and promote the construction industry to develop in a greener and low-carbon direction.

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